GEOLOGY OF THE LOWER CRETACEOUS MANNVILLE GROUP AS A SOURCE OF WATER AND A RESERVOIR FOR BRINE DISPOSAL

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FINAL REPORT

BY

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EXECUTIVE SUMMARY

The Early Cretaceous Mannville strata comprise relict bodies laid down as fluvial and tidal channel-fill sandstones and mudstones, beach sandstones, lagoonal and estuarine mudstones, marsh and swamp claystones, soils and peats and offshore marine sheet sandstones, siltstones and shales. Low depositional gradients permitted a shingle-like accumulation and layering of these laterally short-ranging bodies, and thus, to hydraulic continuity over larger regions.

Reservoir sands of the Vanscoy district are distributed (1) as an east-west mass across the district and (2) as a 2 km wide northwesterly band west of the CM&R 11-16 pilot hole. Total accessible pore volume is $1.04 \times 10^9 m^3$.

The major structural form is a monocline, dipping southwesterly and dissected into terraces by northwesterly and northeasterly troughs. Linear elements such as these and the associated joint pattern exercise control on Mannville depositional patterns, differential structural movement and even the system of the North and South Saskatchewan Rivers. Karsting of the Devonian salt beds by meteoric water invasion from the southwest, contributed most to pre-Mannville and post-Mannville structural relief.

Hydraulic regime of the Mannville is held in common with the Upper Devonian down to the base of the Wymark Member of the Duperow Formation. Effective permeability of the Mannville is 188 md and hydraulic conductivity is 2.3×10^{-4} cm/sec. Gradient is to the northeast and flow is estimated at 3,144 m^3/day across the 1.6 km front.

Volume for volume replacement of the Mannville Formation water (50,000 ppm) with brine (350,000 pp.m) would lower the potentiometric head at the storage site. Also brine by its greater density, would eventually move downward in the hydraulic column through the fracture system to the Wymark Member. Migration to the northeast

would be slowed to about 80 percent of the current rate.

Impacts are (1) the volumetric increase accompanying brining; the excess will have to be disposed of elsewhere to avoid over-pressuring the Mannville; and (2) increased loading of the Mannville reservoir may increase the static pressure on the abandoned mine galleries.

RESUME

La formation Mannville du Crétacé inférieur contient des corps résiduels déposés en tant que grès et argile fluviatils et de remplissage de chenaux tidaux; grès de plage; argiles de lagon et d'estuaires; argilite de marais et de marécage; sols et tourbes; grès, silts et schistes argileux stratifiés de dépôts marins côtiers. Des gradients de sédimentation lente ont permis une accumulation en échelon et un litage de ces corps qui ont une faible extention latérale et donc une continuité hydrologique sur des régions plus grandes.

Les sables du réservoir du district de Vanscoy sont distribués 1) comme une masse est-ouest traversant le district et 2) comme une bande nord-ouest de 2 km de largeur à l'ouest du trou pilote CM&R 11-16. Le volume accessible total des pores est de 1,04 x $10^9 m^3$.

Le relief structural majeur se présente de façon monoclinale avec un pentage sud-ouest et est disséqué en terrasses par des dépressions d'orientations nord-ouest et nord-est. De tels éléments linéaires et le réseau de fissures associées contrôlent les systèmes de dépôt de la formation Mannville, un mouvement structural différentiel et même le réseau des rivières Saskatchewan nord et sud. La karstification des niveaux salifères du Dévonien par l'invasion d'eau météorique en provenance du sud-ouest est en grande partie responsable de la formation du relief structural pré-Mannville et post-Mannville.

Le régime hydraulique de la formation Mannville est commun avec celui du Dévonien supérieur jusqu'à la base du membre Wymark de la formation Duperow. La perméabilité effective de la formation Mannville est de 188 md et la conductivité hydraulique est de 2,3 x 10^{-4}cm/sec. Le gradient est dirigé vers le nord- est et le flux est estimé à 3.144 m^3/jour sur un front de 1,6 km.

Le volume pour remplacer le volume d'eau de la formation Mannville (50 000 pp.m) par des saumures (350 000 pp.m) abaisserait la pression potentiométrique sur le site de stockage. Les saumures, également par leur grande densité, descendraient par la suite dans la colonne

hydraulique à travers le système de fractures du membre Wymark. La migration vers le nord-ouest diminuerait à à peu près 80 pour 100 du débit actuel.

Les conséquences sont 1) l'accroissement volumétrique accompagnant la formation des saumures; on devra se débarasser de l'excédent pour éviter une surpression de la formation Mannville; et 2) l'augmentation de la charge du réservoir Mannville pourrait accroître la pression statique dans les galeries de mines abandonnées.

INTRODUCTION

PURPOSE OF STUDY

To undertake a detailed study from the available data of the region around the Cominco Potash Operations in order to determine:

1) the geological environment of the Lower Cretaceous Mannville Formation;
2) the factors bearing on the formation as a reservoir water source and brine storage, and
3) the potential impacts of implementing (2).

AREA OF STUDY

Area of detailed study is located in Township 35 of Range 8 and 9 west of the Third Meridian, in context of the region enclosed by Township 31 and 41 and Ranges 5 and 12 west of the Third Meridian, Saskatchewan. Topographically, the region is flanked to the north by the North Saskatchewan River and to the east by the South Saskatchewan River. It includes the city of Saskatoon and the towns of Delisle, Vanscoy, Grandora and Asquith among others. (Fig.1)

SCOPE OF STUDY

The available data from 102 wells in the region were utilized. These are mostly geophysical well logs, drill stem tests data and well cuttings. As well, the 3 full length cores of the Mannville, CM&S Vanscoy 11-16-35-8W3, Duval Saskatoon 6-18-36-6W3 and Goldfield Grt. Cnd. Dundurn 10-7-35-5W3 were logged in detail and used to interpret

the sand bodies as reservoirs and for regional correlations. Porosity and air permeability values were determined for the Vanscoy core by Core Laboratories. Porosity values served to calibrate the porosity logs for the Vanscoy district in order to calculate and map volumetric capacity of the formation. The air permeability values served as control for determinations of effective permeabilities from the drill stem tests. The formation water system for the Mannville and the upper Devonian strata was also evaluated from the drill stem test pressure and salinity data in the files.

GEOLOGICAL SETTING

The sandstones, shales and mudstones that constitute the Early Cretaceous Mannville Group of Saskatchewan are part of a vast spread that reaches east from the Rocky Mountains of Alberta to southwestern Manitoba and north from New Mexico to the Arctic in the west and central Saskatchewan in the east.

At the Montana-Saskatchewan border this body of rock lies at a depth of 1200m. It rises northward from the Williston Basin to scattered outcrops along a northwesterly trending belt from the Swan River district of Manitoba, through the Pasquia and Wapawekka hills of central Saskatchewan to the Clearwater-McMurray valleys of central western Saskatchewan and eastern Alberta.

The nomenclature has undergone several changes and parallel usages over the years. The terms "Blairmore, Swan River and Inyan Kara" have had their proponents, but Mannville has been adopted by the petroleum industry of the Alberta plains, especially the Lloydminster region. Its usage has been adopted in Saskatchewan for consistency

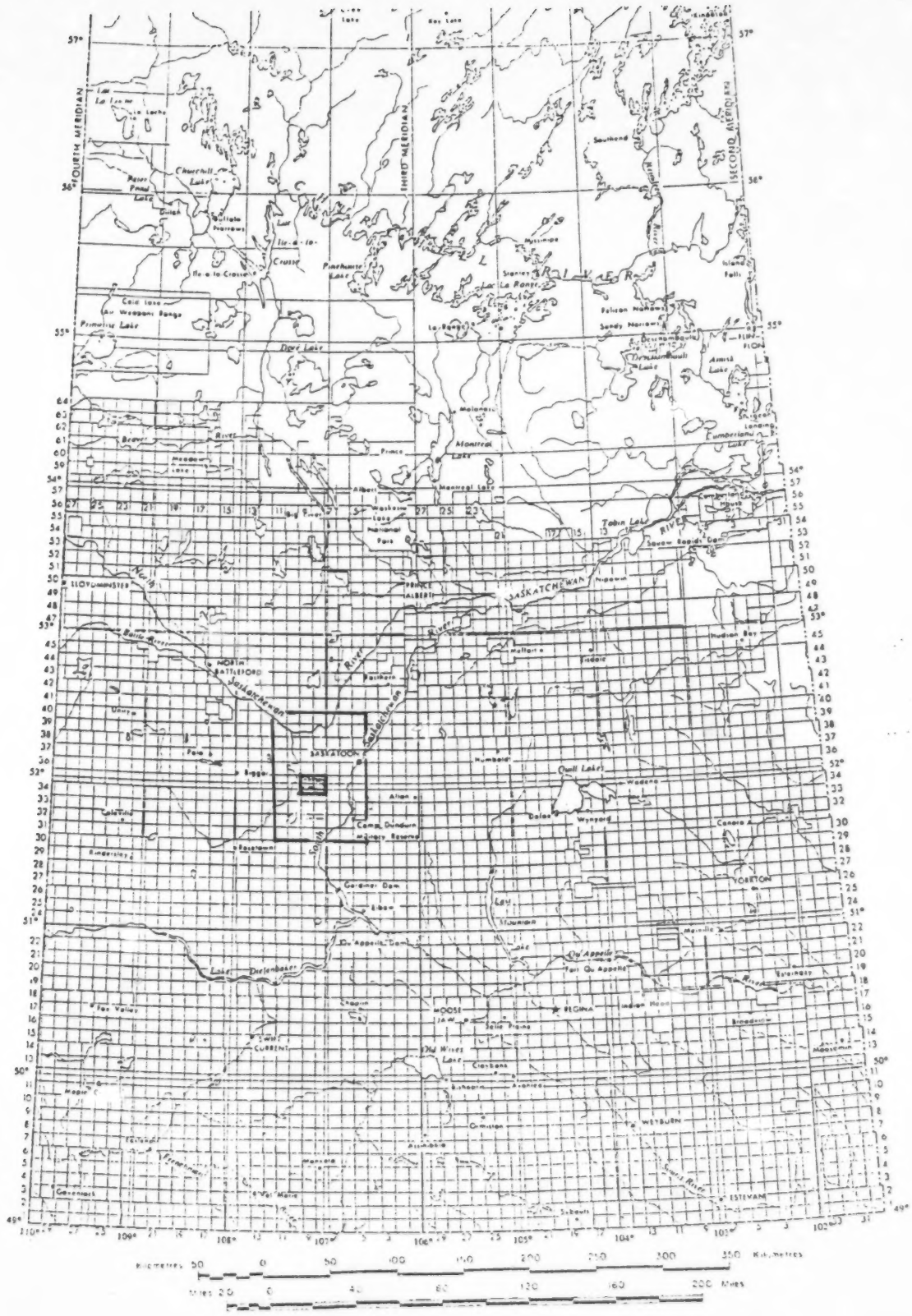

Figure 1. Location Map.

sake (Maycock, 1967, Christopher, 1974) and by the sheer weight of numbers of industry geologists using it. The type section of the Mannville is in the Mannville No.1 well of east central Alberta as defined by Nauss, 1945.

The Mannville of Saskatchewan is everywhere overlain by the Joli Fou Formation of the Colorado Group. On the other hand, it overlies a stripped surface of sub-cropping strata ranging from the Upper Jurassic in the south to Precambrian near Lac La Ronge and Churchill Lake. In the study region the subjacent strata from south to north are the Upper Devonian Torquay, Birdbear and Duperow Formations.

Because of the relief on the erosion surface thickness of the Mannville Formation ranges locally from less than 15m to more than 100m. Generally, the range is from 75m in the south to 240m in central western Saskatchewan. Additionally, Mannville thickness is affected by syn-depositional faulting along basement-controlled linears, by collapse of underlying strata into salt sinks of the Middle Devonian evaporite beds and regionally, by intraformational erosion.

STRATIGRAPHY

GENERAL SETTING

A stratigraphic column from ground surface to the Cambrian Deadwood Formation based on the Midas No.3 well (Lsd. 14-28-38-6W3) is depicted in Figure 2. (after S.Whitaker 1970 in Christiansen, 1970)

The Mannville sandstones and shales are underlain by some 1060m of Paleozoic strata, most of which are limestones,

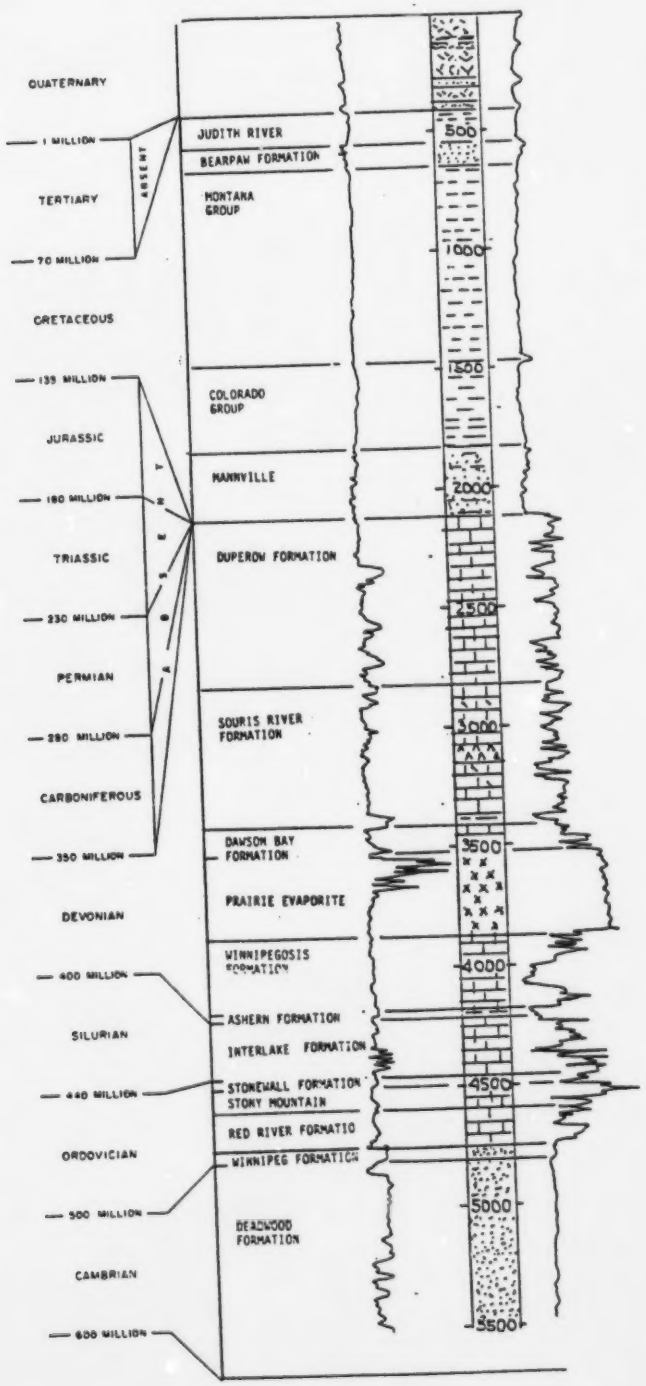

Figure 2. Stratigraphic column at Midas No.3 well; (14-28-36-6W3).

dolomites, shales and evaporites, but include at the base more than 300m of the Ordovician Winnipeg and Cambrian Deadwood sandstones and shales.

Above, about 400m of Cretaceous Colorado and Lea Park shales separate the Mannville Group from 20m of Judith River (Old Man) sandstones which form the base of the ground water system (Christiansen and Meneley, 1971). The Late Cretaceous Bearpaw Shale completes the Mesozoic succession at the sub-Quaternary erosion surface. Because of the high relief on this surface, which in valleys intersect even the Judith River Formation, thickness of the Bearpaw is highly variable.

Inversely, thickness of the Quaternary blanket of sediments also varies, being thickest, up to 150m, in the large preglacial and interglacial valleys. The sediments comprise the Empress Group of preglacial sands and the overlying till, sand and clay sequences.

THE MANNVILLE GROUP

Mannville strata are laid down as a rather even blanket 110 to 130m thick, across two-thirds of the region (Fig.3). Departures from this spread of values reflect pre-Mannville topography or post-Mannville structural events and are most conspicuous east of Range 7W3.

L.Price (1963) introduced the names Cantuar and Pense Formations for the Mannville sequence in southeastern Saskatchewan. The Cantuar Formation is recognized as a heterogeneous assemblage of rock types laid down in a mixed continental and near-shore marine environment. It comprises the bulk of the Mannville section in the region of study. The overlying Pense Formation, though up to 45m thick in the southwest of the province, here in the

study region forms only a minor sub-division, 13 to 15m thick. Except for a few localities permeable sandstones are scarce.

CANTUAR FORMATION

Morphologically, Cantuar strata belong to bodies laid down as fluvial and tidal channel-fill sandstones and mudstones, beach sandstones, lagoonal mudstones, marsh and swamp claystones, soils and peats, and offshore marine sheet sandstones, shaly silts and shales. Because the depositional slopes on which these sediments were laid down were low, and there were many advances and retreats of the shore, as the basin was filled, only relict sedimentary deposits remain.

Thus individual rock bodies are seldom traceable beyond a kilometre or two. Their shapes and trends are derived from their depositional formats. For instance, channel and beach sand bodies tend toward linearity, but at the same locality the trend of one will be oblique to perpendicular to the other. Again, shore-controlled sandstones are apt to reflect the shoreline geometry whether or not it be linear or curvilinear as in an embayment.

On the other hand, the low depositional gradients permitted a shingle-like layering of these laterally short-ranging bodies, and thus, in most instances, to hydraulic continuity over larger regions.

Recognition of the overall cyclical nature of Mannville sedimentation in the Lloydminster heavy oil producing district (Fuglem, 1970, Vigrass, 1968) has led to a nine-unit sub-division of the Group. Six of these units have been correlated by the author with the Cantuar Formation and are introduced to the region of study as (0-Y) the Dina, Cummings, Lloydminster, Rex, General Petroleum and

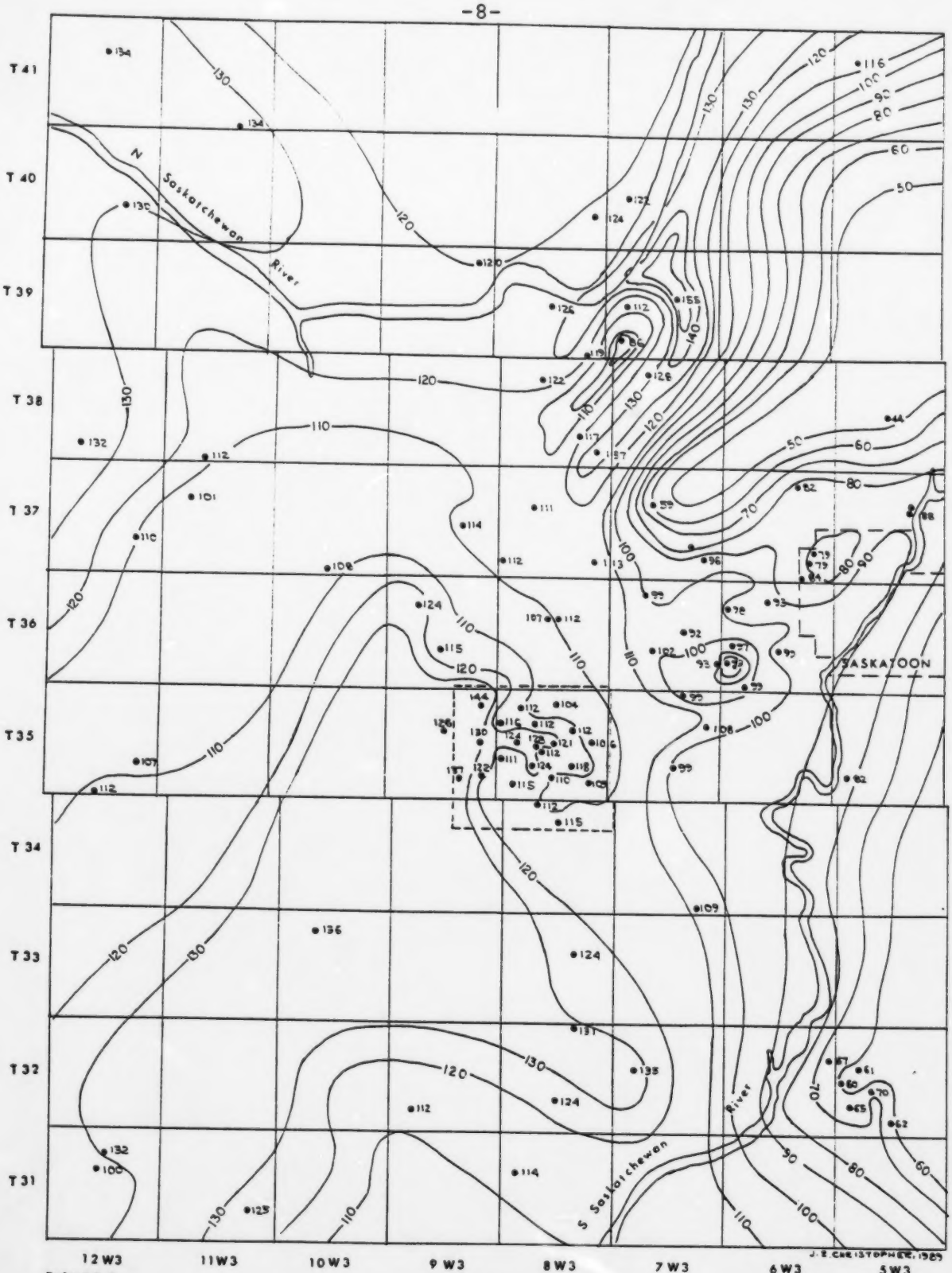

FIGURE 3
ISOPACH MAP
MANNVILLE GROUP
VANSCOY-CORY REGION
SASKATCHEWAN

Scale 1:250,000 Échelle

C.I. = 10 M

Waseca. Descriptions of these units as summarized below are based on detailed logs of the full cores from the CM&S Vanscoy 11-16-35-8W3, the Duval Saskatoon 6-18-36-6W3 and the Goldfields Gnt Cnd Dundurn 10-7-32-5W3 wells. The geophysical log for the Vanscoy well is depicted in Figure 4. Depth intervals are as listed.

Dina Unit (Interval 2056-2073 feet)

The Dina unit at the Vanscoy site comprises a fine to very fine grained quartzose sandstone indurated in a dark grey mudstone matrix with abundant carbonaceous plant fragments near the base. It is 5.8m thick. Good porosity and permeability are restricted to the upper 1.5m. At the Saskatoon and Dundurn sites, however, the Dina is less occluded with clay , and features the more typically cross-bedded permeable sands interbedded with carbonaceous silts and clays. Thicknesses are 7 and 13m respectively, and porosity and permeability are good.

Variability in thickness and sand quality are characteristic of the Dina, which typically fills in depressions and valleys of the sub-Mannville erosion surface (Fig.5). Thicknesses range from 0 to 49m. The isopachytes delineate a 75- to 100km-wide rectangular depression forming a low saddle from which wide valley-like forms radiate on the diagonals of the quadrant. The Dina is absent on the overlooking uplands.

The northern valley appears to have entered the region from the northwest and to have left in the northeast as a stream following cuestas of the Duperow Formation. Its northeastern arm coincides with the course of the North Saskatchewan River. In contradistinction to the north side of the saddle, the valleys on the south side appear to

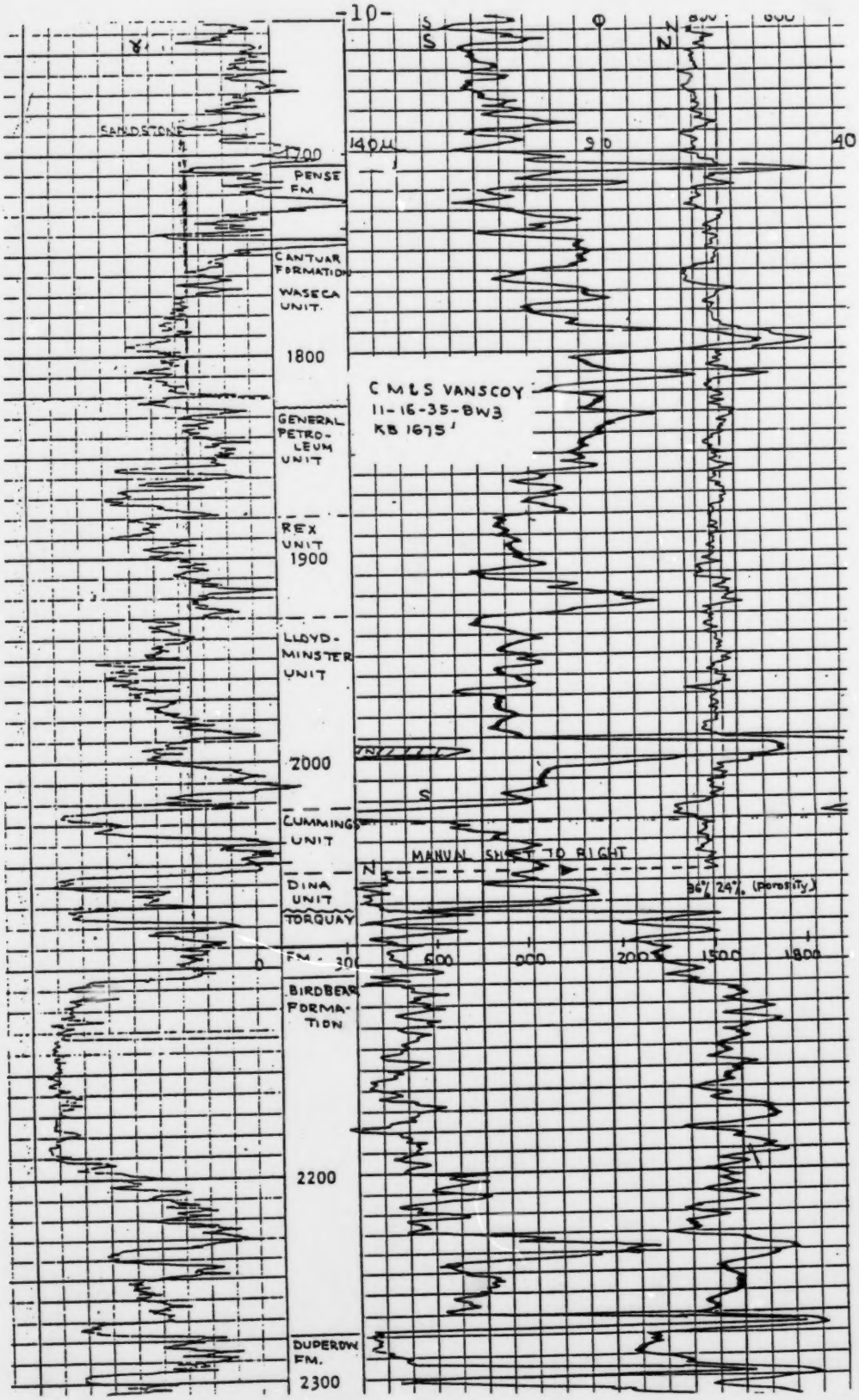

Figure 4. Gamma Ray-Sonic-Neutron log of the Mannville and Birdbear Formations, CM&S Vanscoy 11-16-35-8W3.

to have been initiated against the crest of the saddle and directed to the southeast. Like its northern counterpart the trend of the southeastern valley-form presages the course of the South Saskatchewan River.

One may dedeuce from the foregoing that the Dina depositional basin represents a breached anticline, the northern and southern flanks of which were down-warped by retreat of the salt dissolution fronts of the Prairie Evaporite. This activity preceeded the influx of Dina sediments, which followed as a product of passive infill, initially by mature streams combatting the Early Cretaceous sea invading the lowlands.

Cummings Unit. (Interval 2024-2056 feet)

These deposits represent the earliest of the Mannville shale-sand couplets. In the area of study the sandstone overlies the shale and spreads across the upland flats as marine sheets.

At the Vanscoy site the Cummings sandstone is typically for the region, fine grained, well sorted, silica grain-contact cemented, current-bedded and includes about 15 percent of black shale partings. It is relatively thin at 3m. The sandstone overlies 6.4m of grey black silty shale and black shale and is capped by 1.7m of lignitic shale. Toward the Saskatoon site these shales yield to sand to form a largely sandstone unit 5.5m thick. At Dundurn this sandstone is 4m thick on a similar thickness of shale. This consistency is traceable through most of the wells in the area of study.

Lloydminster Unit. (Interval 1926½-2024 feet)

At the Vanscoy well the Lloydminster unit consists of

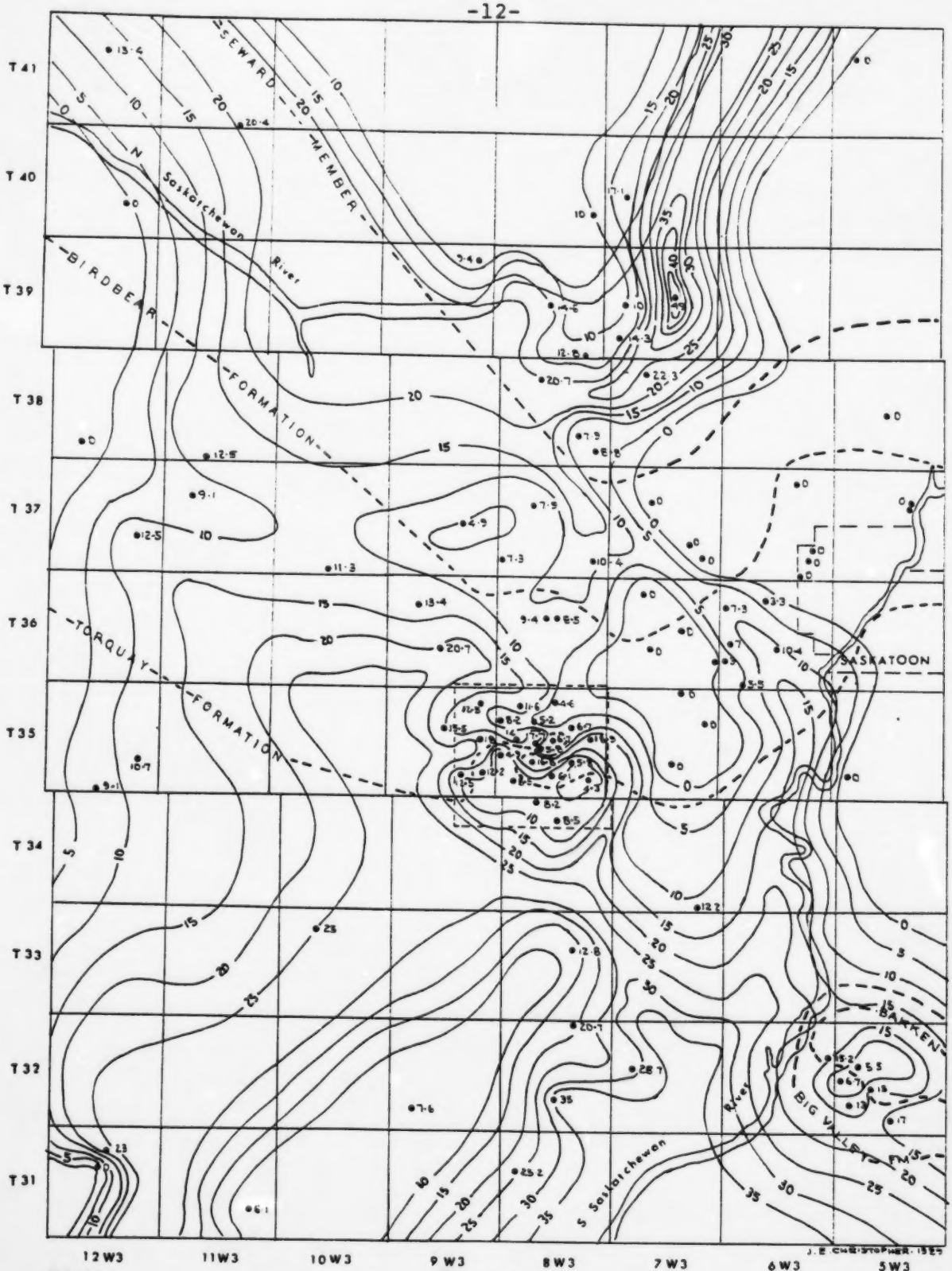

FIGURE 5
ISOPACH MAP
DINA UNIT
VANSCOY-CORY REGION
SASKATCHEWAN

Scale 1:250,000 Échelle

C.I. = 10 M

two bedding groups: the one comprising 4 cycles of sediments coarsening upward from dark grey shales through transitional lenticular and podded, silty shales, in part bioturbated; to fine, quartzose, weakly argillaceous and rootlet-burrowed indurated sandstones near the top. Two of the cycles are capped with thin lignite and lignitic shale. This bedding group occupies the lower one-half of the unit (1990-2024 ft) in a thickness succession of 2.4, 3.4, 4.3 and 4.6m.

The other at 1931 to 1990 feet consists of fining-upwards sequences: (1) A thin lower (1.7m) bed ranging from very fine to silty quartzose sandstone, poorly indurated, and grading upward to rootlet burrowed, carbonaceous mudstone capped with lignitic shale; and (2) a thick upper (11.4m) subunit dominated by alternations of trough cross-bedded, very fine grained quartzose sands and thin black shale. Scattered glauconite occurs in the lower part of the sequence.

A medium dark lavender grey mudstone with abundant plant fragments form a 1m top to the Lloydminster unit.

The first bedding group is typical of prograding deposits laid down in response to episodic deepening or rising of the sea. The second bedding group is interpreted as channel fill; the one fluvially dominated the other estuarine to marine delta front.

This bipartite stratigraphic arrangement of prograded marine sandstone sequence-groups underlying a channel facies sequence-group is not constant from one part of the region to another.

At the Saskatoon well there is a 4-part alternation of the sequences begining with the channel body in a thickness succession of 3.7, 5.8, 7.7 and 3m.

There are 2 bedding groups at the Dundurn well as at the

Vanscoy well, but each group represents only one cycle; 3m of progradational very fine quartzose sand overlain by 3.6m of channel facies. On the other hand, the capping mudstone layer is 6.2m thick.

With respect to depositional format, one dedeuces a deltaic to marine transition of coastal sands, bay muds and silts, onshore marshes, lagoons and distributary channels opening to the sea. In the absence of wave-washed beach sands, the marine sands are likely of irregular shape, most probably discoidal. The channel sands would be linear to serpentine. The low depositional gradients indicated by the thinness of the sedimentary bodies suggest rapid shift of depositional loci and therefore the likelihood of shingled layering of sandstones. Local stacks of unicomponent deposits also occur as indicated by the upper marine channel sandstone at the Vanscoy well and the thick mudstone bed capping the unit at the Dundurn well.

Rex Unit. (Interval 1879-1926½ feet)

The Rex unit at the Vanscoy well is an overall upward coarsening, bioturbated, current bedded succession represented by a lower subunit, 5.4m thick, grading from laminated grey-black shaly siltstone to a silty sandstone; and an upper subunit, 3m thick of very fine grained sandstone, argillaceous toward the base. Each subunit is capped by a lignitic shale about 0.3m thick. At the Saskatoon well the same pattern persists but is repeated over three subunits, 2, 3.3, and 3m thick. However, at the Dundurn well, only 2.6m of the Rex is present and consists of a single upward transition from laminated siltstone to a medium and fine grained, bimodal sandstone with small scale, low angle truncation sets.

Thus the Rex unit is fairly consistent in its bedding format. Variations in thickness as at the Dundurn site appears to be a function of downcutting from the overlying horizon. Depositional environment is taken as marine embayment with flats interrupted by channels, perhaps tidal inlets as at Dundurn.

General Petroleum Unit. (Interval 1827½-1879 feet)

Overall coarsening upward of the grade sizes is also apparent in the General Petroleum unit at the Vanscoy well. Three bedding groups are identified (O-Y):

1. Glauconitic, pyritic, bioturbated laminated black shale, and grey, current-and trough cross-laminated fine and very fine grained quartzose sandstone; inter bedded with laminated shale and sandstone. Basal contact is sharp and irregular. Thickness is 11m.
2. Glauconitic and bioturbated shale and siltstone interbeds, 1m thick, overlain by 2.8m of well sorted, fine grained, trough cross-and-flat-laminated sandstone with abundant plant detritus coating layers; and
3. upward coarsening sequences, 8.8m thick, of carbonaceous burrowed mudstone, and current bedded, flasered, black mud draped, burrowed siltstone, 8.8m thick.

There are also 3 bedding groups in the section at the Saskatoon well:

The lower subunit comprises 4m of well sorted, very fine grained, quartzose sandstone with low angle truncation sets lined with carbonaceous detritus and fining upward into 0.6m of laminated black and grey shale and siltstone.

The medial subunit includes 1.5m of interbedded, poorly sorted argillaceous sandstones (sandy loam) and contorted mudstone, under 3.9m of a sequence coarsening upward from dark grey siliceous shale, through glauconitic interbedded shale and ripple-laminated very fine grained quartzose sandstone into sandstone, very fine grained and massive. About 1.5m of rootlet-burrowed green-grey claystone, sandy siltstone and caliche layered and cemented sandstone complete the sequence. Well sorted, very fine grained quartzose sandstone, interlayered over the lower one-half with burrowed, argillaceous, ripple current-bedded sandstone constitute the 3.4m thick upper subunit.

The General Petroleum at the Dundurn well is a 9.4m unit of massive, medium grey mudstone with carbonaceous plant detritus and pyritic nodules at the base.

Depositionally, the bedding groups of the General Petroleum reflect aggradation in a basin that was warping differentially. The sandstones of fining upward and coarsening upward sequences are similar; the former appearing to be drowned equivalents of the latter. The medial units at Vanscoy and Saskatoon both indicate similar episodes of deposition at the water-atmosphere interface, and fluvial channel sands and scoured contacts support this. The lack of a well defined sandstone at the Dundurn site and the general massiveness of the mudstone imply sediments settling out in a quiet water environment, possibly a lake or wide channel. It would appear that the shore front environment of the Rex unit shifted landward in General Petroleum time to include more of the coastal plain. Thus over the larger region of study, permeable sand bodies are apt to be discontinuous. In the northern part of the region however, General Petroleum sandstones do form continuous bodies up to 18m thick; but in the south variability seems to be the rule.

Waseca Unit. (Interval 1827½-1742½ feet)

Three bedding groups of compound fining upward sequences define the Waseca unit at the Vanscoy well. The unit fines upward overall, from a basal conglomerate through mudstone-interrupted grit and medium sand sequences into massive mudstone and claystone at the top.

Bedding group 1 rests on a sharp erosional contact, with relief exceeding 3cm over 4-inch diameter of the core; and features 2.6m of a conglomerate of flat mudstone pebbles and grit in a matrix of coarse grained, kaolin-indurated quartzose sandstone. The large clasts are of kaolinite, iron-stone and tree limbs. A thin (0.6cm) lignitic shale caps the subunit.

Bedding group 2 grades upward from grit, through coarse to medium grained kaolin-indurated sandstone. Trough cross-bedding yield to ripple and current bedded black shale-draped laminae. Thickness is 5.2m.

Bedding group 3 features a 5.2m transition from medium grained white kaolinite-indurated quartzose sandstone with subordinate dark grey chert and black carbonaceous grains, and a basal mudstone conglomerate, to fine grained, argillaceous, quartzose sandstone. The sequence is terminated by 8.7m of purplish grey claystone and sphaerosideritic mudstone.

Coarsening upward sequences as exemplified by the preceeding Mannville units form the first and second of 3 subunits in the Waseca of the Saskatoon well.

The lower 8.5m thick subunit displays a grey-black shale, irregularly laminated and thinly interbedded with subordinate very fine grained quartzose sandstone. The sandstone is lenticular, wavy and starved-rippled, laminated and podded. It grades upward into a bioturbated, very fine

grained, contorted argillaceous, quartzose sandstone; and is capped by thin mudstone with carbonized rootlets.

The medial subunit comprises 3.4m of well sorted, very fine grained, current-bedded, weakly indurated quartzose sandstone with minor laminae of dark grey shale. Bioturbated traces and black shale drapes are abundant over the lower one-half. Lavender-grey claystone and mudstone, 8.3m thick, with abundant coarse sphaerosiderites, and an overlying 3m of quartzose, poorly bedded, light grey quartzose sandstone, fining upward to fine from medium, with coarse grained sphaerosiderites complete the section.

The Waseca unit is not present at the Dundurn site where it is lost to the sub-Pense unconformity.

The coarsening upward Waseca deposits present the classical profile of fluvial point-bar sands and inter-distributary channel and interchannel mud flats. Apparently the river system did not penetrate the Saskatoon site until late in Waseca time. The fluvial sandstones are typically clay occluded, and where permeable tend to be limited in extent.

SUMMARY

It is apparent, by review of the core information and geophysical log data, that the near shore marine and deltaic marine sands, whether or not sheet and channel sands, tend to be well sorted, though with variable argillaceous content, and on the whole with permeability suitable for reservoirs. Moreover they tend to be laterally extensive, though not necessarily as continuous sheets. On this basis the good

reservoir sandstones are in the Cummings, Lloydminster, Rex and General Petroleum units.

The fluvial sandstones, on the other hand, though of larger grade sizes and therefore with a potential for better permeability, are generally clay-bonded and therefore poor candidates for reservoir status. In the Vanscoy district, the Waseca unit consists wholly of fluvial sandstones and mudstones and is accordingly discounted.

MANNVILLE RESERVOIR UNITS-VANSCOY DISTRICT

Volumetric Determinations

Porosity determinations were made on core plugs from the CM&S Vanscoy 11-16 well for the Lloydminster, Rex, General Petroleum and Waseca units (Table 1). Porosity values range from 23.1 to 32.8 percent. By comparison with corresponding air permeabilities analysis, similar porosities are not all equal. Permeability ranges from 3.90 to 526.0 millidarcies, and is apparently a function of the argillaceous component of the sandstone matrix.

The porosity-permeability values were plotted on the gamma ray-sonic-neutron log of the Vanscoy well. The gamma ray log was used to separate the less argillaceous sandstones and shales. The porosity values were used to calibrate the sonic-neutron logs. In general, sandstones with porosities less than 20 percent were deleted.

The remainder in the range of 20 to 36 percent were multiplied by their thickness and summed for each unit. The process was repeated for the 24 wells in the district. Isoporosity maps were thus constructed for the reservoir units Dina-Cummings, Lloydminster, Rex and General Petroleum (Fig. 6-9 inclusive). An isoporosity map of the combined units is displayed in Figure 10.

Table 1. Core Analytical Data. Cantaur Formation, CM&S Vanscoy 11-16-35-8W3.

UNIT	DEPTH (FEET)	PERMEABILITY (AIR,MD)	POROSITY (PERCENT)
Waseca	1784.0	3.90	23.1
General Petroleum	1867.5	526.00	29.9
Rex	1883.5	245.00	31.6
Lloydminster	1936.5	61.1	32.8
	1946.0	32.9	27.7
	1963.0	16.8	23.7

The maps show not only the porosity-metre values at each point but also the porosity trends for the district. Volumetric capacity for each unit was calculated thusly:

1. Area: 36 sections of Township 35, Range 8W3 the 12 eastern sections of Township 35, Range 9W3 and the northern 6 sections of Township 34, Range 8W3, for a total of 54.
2. Each section was assigned a porosity-metre value based on the average of the wells in or adjacent to it.
3. Sections on the perimeter of the contoured region were assigned a value based on the contour through them.
4. Total volume of the unit is the average porosity metre of the area multiplied by the total area, in square metres.

Dina-Cummings Unit (Fig.6)

The Cummings unit is the most consistent of the sandstone sequences in the Vanscoy district, and maintains a relatively uniform porosity thickness of 1.0-2.0m. Additionally it tends to thicken over the sub-Cantaur erosional highs.

Variability in thickness and sandstone quality characterize the Dina unit. The thicker deposits reflect the sub-Dina topographic depression, and are more often than not, poorly sorted with high clay content. Nonetheless, sandstones higher in the unit locally approach good reservoir quality.

The isoporosity 4m thick trending northwest from CM&S Vanscoy 16-8 through the wells 4-20 and 4-30 drape the crest of a sub-Mannville topographic rise, and probably represents a vast sand shoal or bar.

Average porosity thickness = 114.4m/54 = 2.19m

Total volume (m^3) = $2.19 \times 139.9 \times 10^6$

= 3.06×10^8

Lloydminster Unit (Fig.7)

Lloydminster porous sandstones are best developed above the domes of the sub-Mannville topography. They form a broad mass distributed east-west across Township 35, Range 8 and 9 west of the Third Meridian. Another such body is suggested to the south in Township 34. Porosity units attain thicknesses of 6m, which are the maximum for the Mannville units in the district.

Average porosity thickness = 167.9/54 = 3.11m

Total volume (m^3) = $3.11 \times 139.9 \times 10^6$

= 4.35×10^8

Rex Unit (Fig. 8)

Similar in distribution to the Lloydminster but thinner, Rex high-porosity sandstones could be naturally combined with the Lloydminster as one hydraulic unit.

Average porosity thickness = 57.2/54 = 1.06m
Total volume (m^3) = 1.4×10^8

General Petroleum Unit (Fig. 9)

Porosity trends of the General Petroleum unit are comparable with those of the Cummings-Dina; i.e., north-westerly and linear. However, there is a pronounced difference. General Petroleum isoporosity thicks conform to thins in the basal unit. In that inter-shoal or channel sands, as the case may be, tend to be muds, the inverse relationship may be the expression of complementary basin infill. General Petroleum sands have filled compaction lows.

Average porosity thickness = 68.1/54 = 1.26m
Total volume (m^3) = 1.8×10^8

Combined Cantaur Porosity Units (Fig. 10)

The porosity distribution of the combined aquifer units reach maximum thickness in Township 35, Range 8W3, where values of 12 to 17m are displayed. Regional values outside the Township fall to between 7 and 10m. A north-south linear thin dissects the central porosity mass into eastern and western reservoirs. This is a distribution echoed primarily in the Lloydminster and Rex units.

Average porosity thickness = 391.5m/54 = 7.25m
Total volume (m^3) = 1.01×10^9
Total volume by the addition of unit totals:
= 1.07×10^9

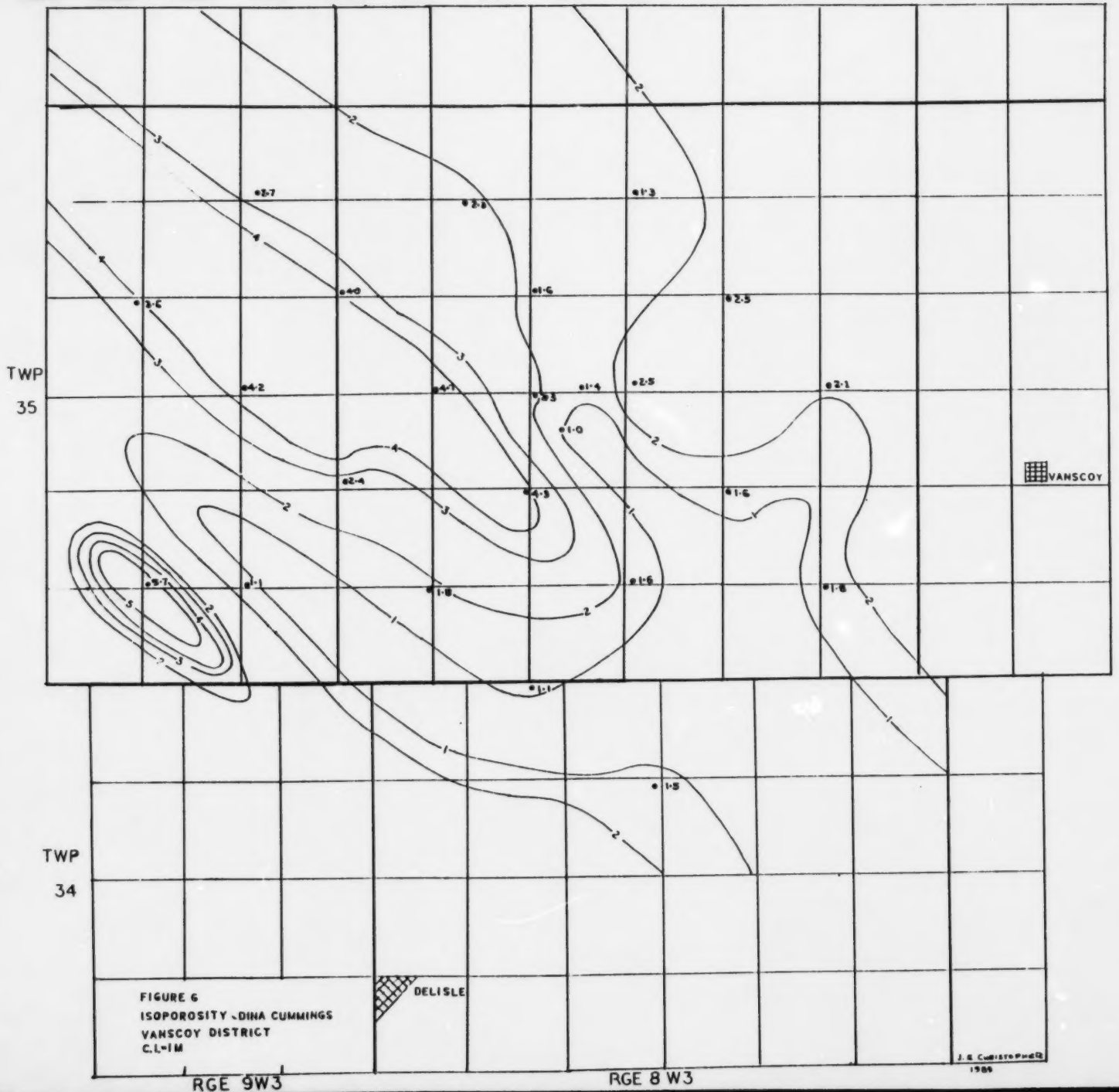

FIGURE 6
ISOPOROSITY - DINA CUMMINGS
VANSCOY DISTRICT
C.I.=1M

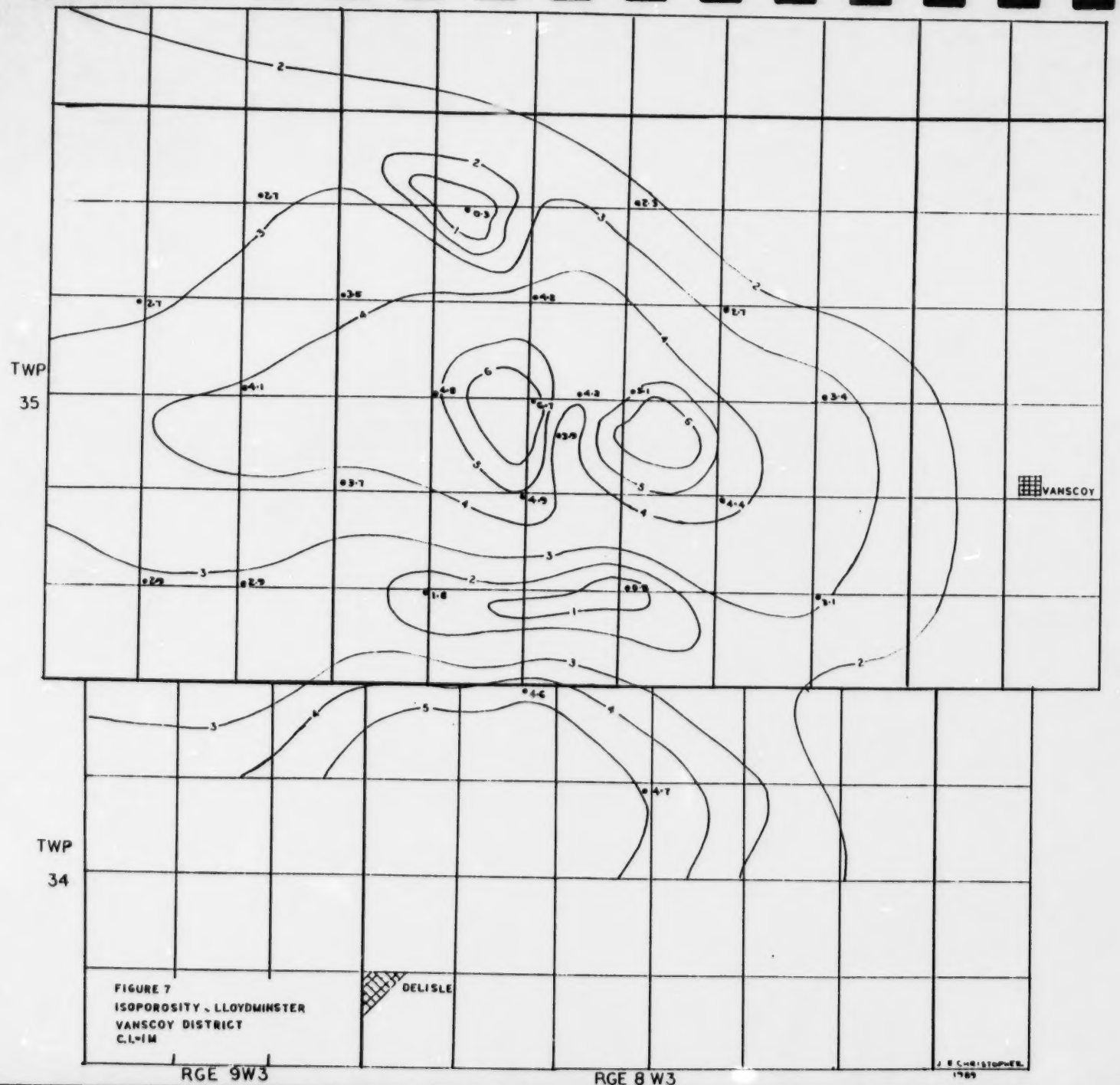

FIGURE 7
ISOPOROSITY - LLOYDMINSTER
VANSCOY DISTRICT
C.I.=1M

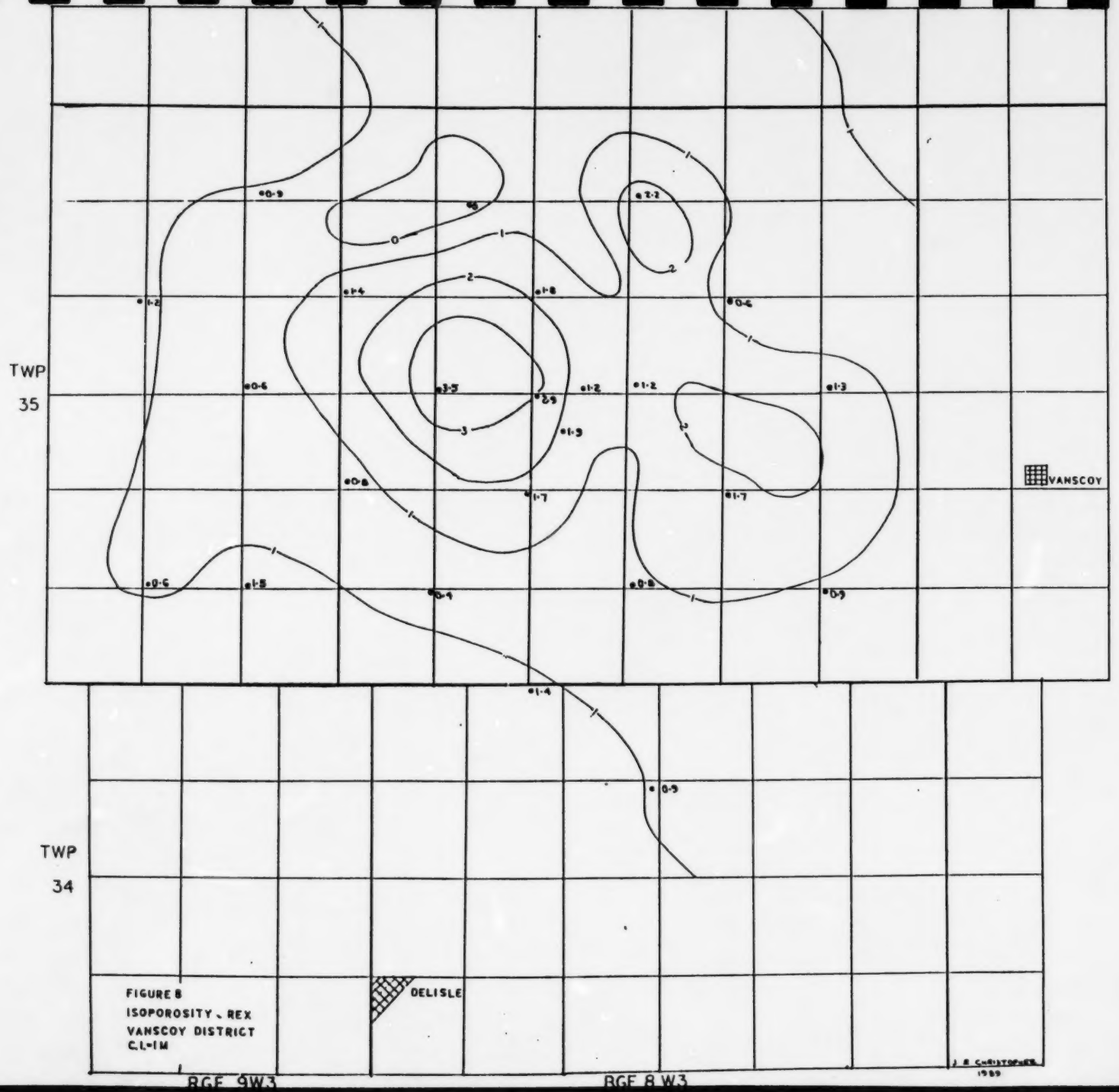

FIGURE 8
ISOPOROSITY - REX
VANSCOY DISTRICT
C.I.=1M

J. R. CHRISTOPHER
1989

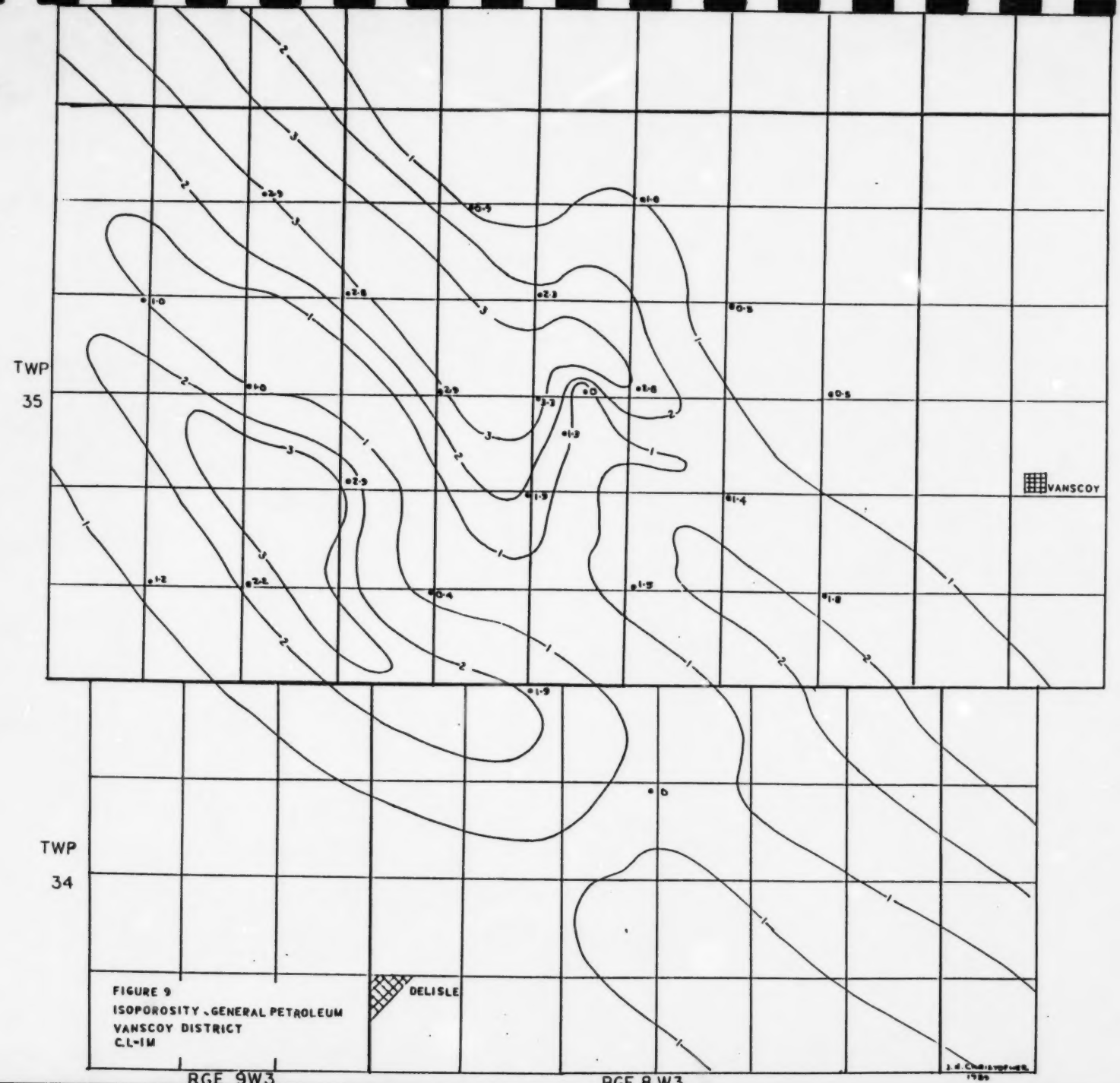

FIGURE 9
ISOPOROSITY - GENERAL PETROLEUM
VANSCOY DISTRICT
C.L-IM

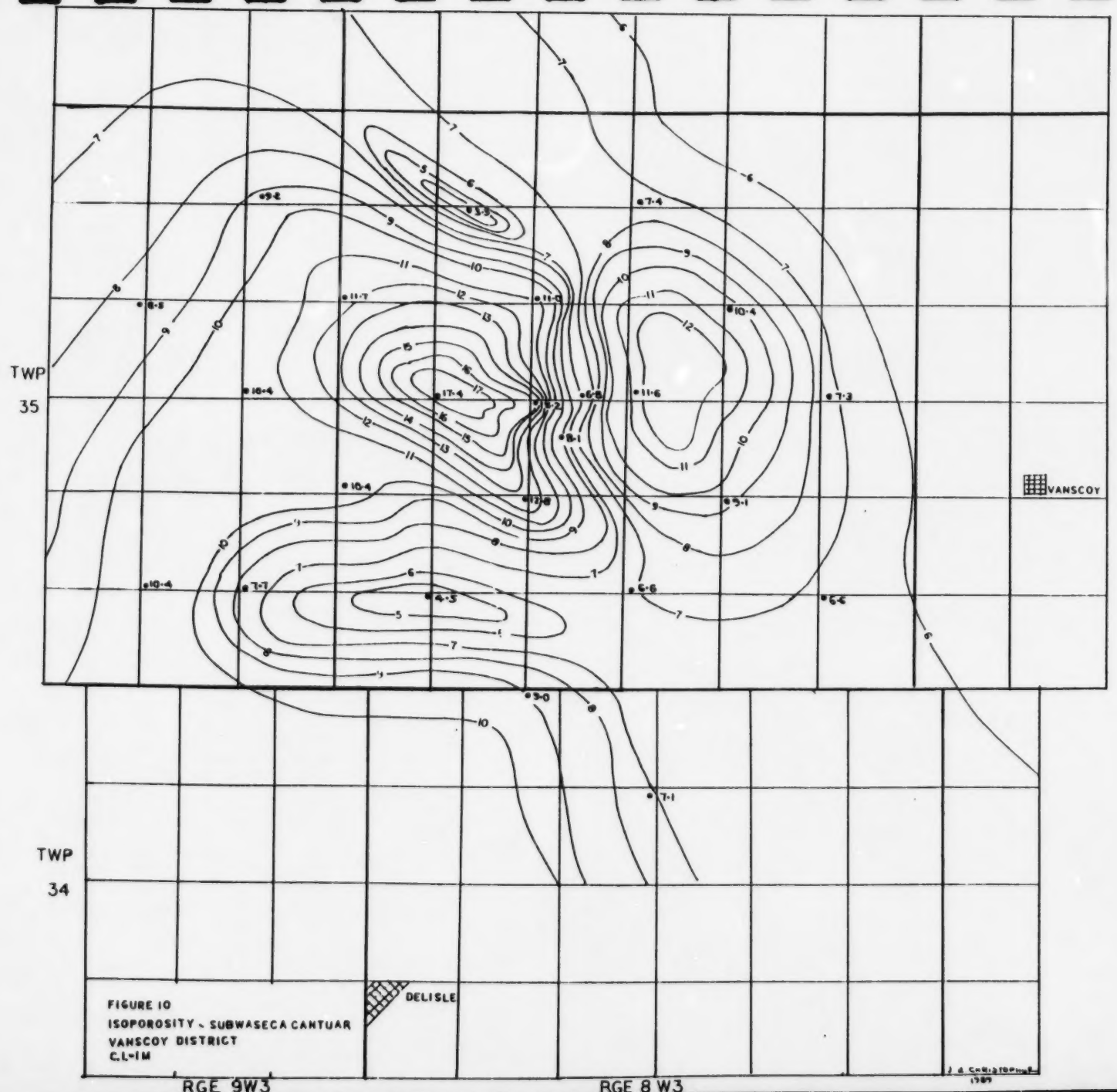

FIGURE 10
ISOPOROSITY - SUBWASECA CANTUAR
VANSCOY DISTRICT
C.I.=1M

Thus the volumetric reservoir capacity of the Cantaur Formation ranges between $1.01 \times 10^9 m^3$ and $1.07 \times 10^9 m^3$ over the 54 sections, for an average of $1.04 \times 10^9 m^3$.

STRUCTURAL GEOLOGY

The Sub-Mannville Surface

The sub-Mannville structure surface of the study area (Fig.11) slopes from elevation -40m in the north to -190m in the south on an overall dip of 3.9m/km or 21ft/mile. It is a monocline, dissected by northwesterly and northeasterly directed troughs into a mosaic of structural terraces.

A trapezohedral terrace, central to the area and containing the Vanscoy and Cory potash mining districts, projects like a peninsula to the southeast from an east-west trough along Township 36. It ends against a steep front along the north-northeasterly trending trough in Range 6W3. Likewise, northwesterly oriented troughs flank the terrace to the east on a line from Saskatoon, and to the west from the scuth-eastern corner of the map area to along the front of the Vanscoy potash district to the northwestern corner of the map area. The terrace dips southeasterly at 2.7m/km or 14.4ft/mile. Flanking relief is 190m on the northeast and southeast and 50 to 60m/km on the southwest and north.

Most of the structural elements depicted on the structure map have pre-Mannville antecedents, in the sense that they appear as topographic features on the isopach map of the Dina unit (Fig.5). However, the topographic relief at 35m is substantially less than the structural extreme of 170m. Only the trough in the northeastern quadrant of the map sheets shows comparable relief. Elsewhere, the change from

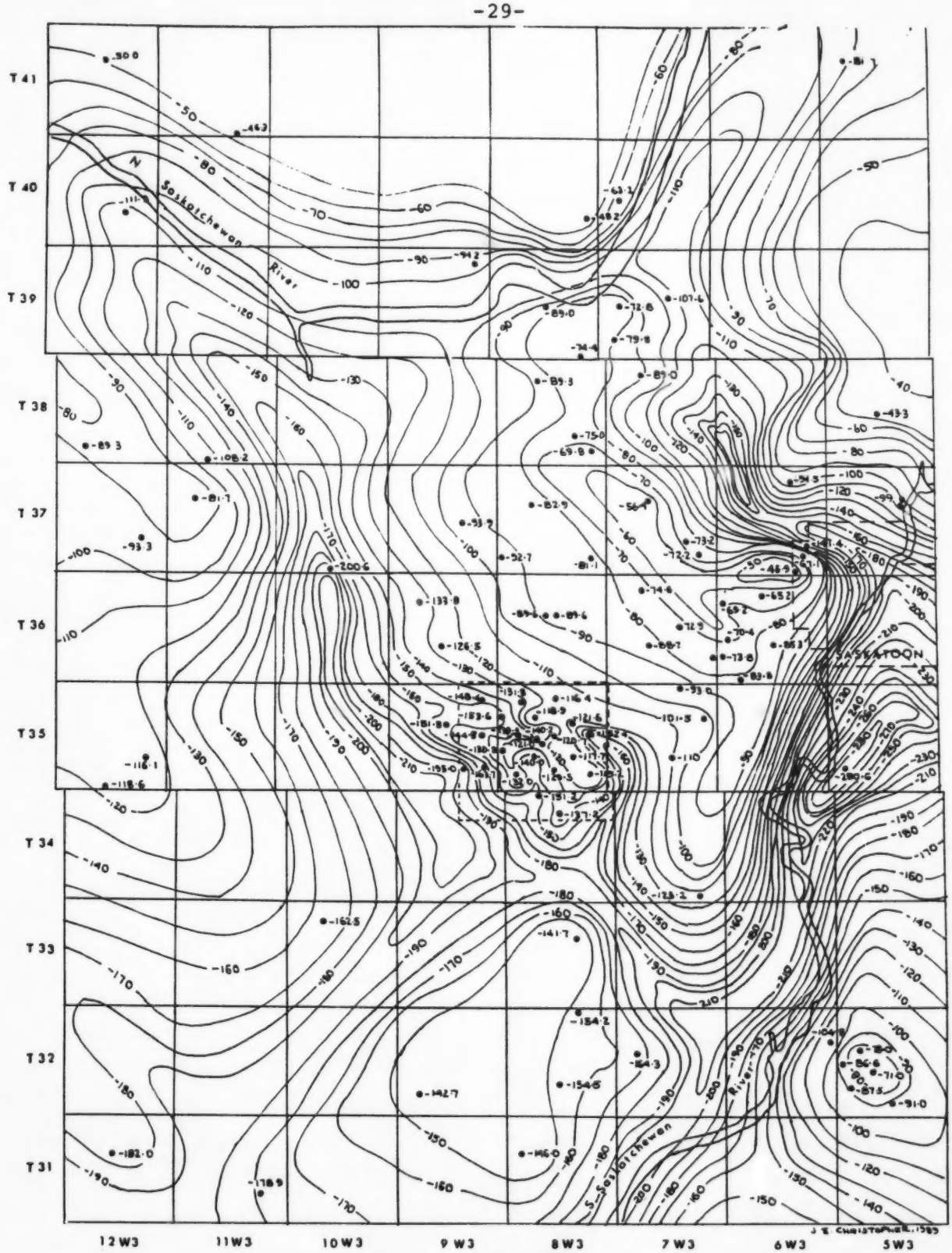

FIGURE II
SUB-MANNVILLE
STRUCTURE MAP
VANSCOY-CORY REGION
SASKATCHEWAN

Scale 1:250,000 Échelle

C.I.-10M

topographic to post-Mannville structural is one of deepening in the troughs and northerly expansion of their extent. The result is a structural grain and relief more pronounced and sharper than the pre-Mannville topography.

Neither the isopachous map of the Dina unit, nor of the full Mannville Group reveals much about the regional Mannville dip. They show an east-west topographic divide across the area in Township 34 to 38 inclusive, and equal relief to the south and north. Thus most of the structural dip is post-Mannville, and in keeping with the rest of the tectonic western plains region, Middle to Late Cenozoic in age.

SALT SOLUTION EFFECTS

Bishop (1956) first applied the hypothesis that intra-stratal water has dissolved and removed in solution large amounts of salt from the Middle Devonian Souris River and Duperow Formations, thereby creating cavities that lead to collapse of overlying beds into them. Thus he explained stratigraphic anomalies in the Venn district east of Saskatoon.

The hypothesis since then has been widely applied to all units above the Prairie Evaporite (Wilson et al 1963-Paleozoic Formations; Christopher, 1961-Three Forks Group; Lane, 1964-Souris River Formation; Kent, 1968-Duperow Formation; Holter, 1969-Prairie Evaporite; Christopher, 1974-Mannville; Christiansen, 1967-Late Cretaceous and Pleistocene).

From a study of the Mannville in southwestern Saskatchewan, it was determined in a comparison of Mannville isopachous and structural differences between adjacent wells, that discrepancies between the two values are attributable to

salt solutioning effects (Fig. 12). In the absence of differential movement between the wells isopachous relief is roughly equivalent to structural difference (allowing for compactional effects). Where structural is significantly greater than the isopachous, the difference reflects post-Mannville subsidence. The reverse indicates an initial pre-Mannville or intra-Mannville solution-collapse at the one point followed by a post-Mannville collapse at the other. Figure 12 illustrates the exercise carried out for the region south of the study area. The relationships depicted hold true for the study area and are demonstrable between any two wells, including those of the mining district.

Linear Elements

Differential movement implies flexuring, fracturing and faulting of the strata involved, preferably along lines of the regional stress field. In this regard, the major troughs and terrace scarps bear northwesterly and northeasterly. These trends are also exhibited by the Saskatchewan River, which in its northeasterly course, tacks northwest and northeast on angular course changes, reminescent of a stream crossing a jointed terrain. Apparently the river is responding to a fracture pattern generated by the large Saskatoon solution collapse depression.

The bearing of the dominant stress direction is suggested by the straight course of the North Saskatchewan River oriented N50^{o}W. This is also the alignment for the western front of the Vanscoy-Cory terrace. The complementary bearing of the set is seen in the northeasterly directed legs of the South Saskatchewan River through Township 32 of Range 6W3 and Townships 36 and 37 of Range 5W3. The bearings of this set are consistent with those reported by Mollard(1988) in an analytical review of fracture systems in Saskatchewan and adjacent regions. In view of the

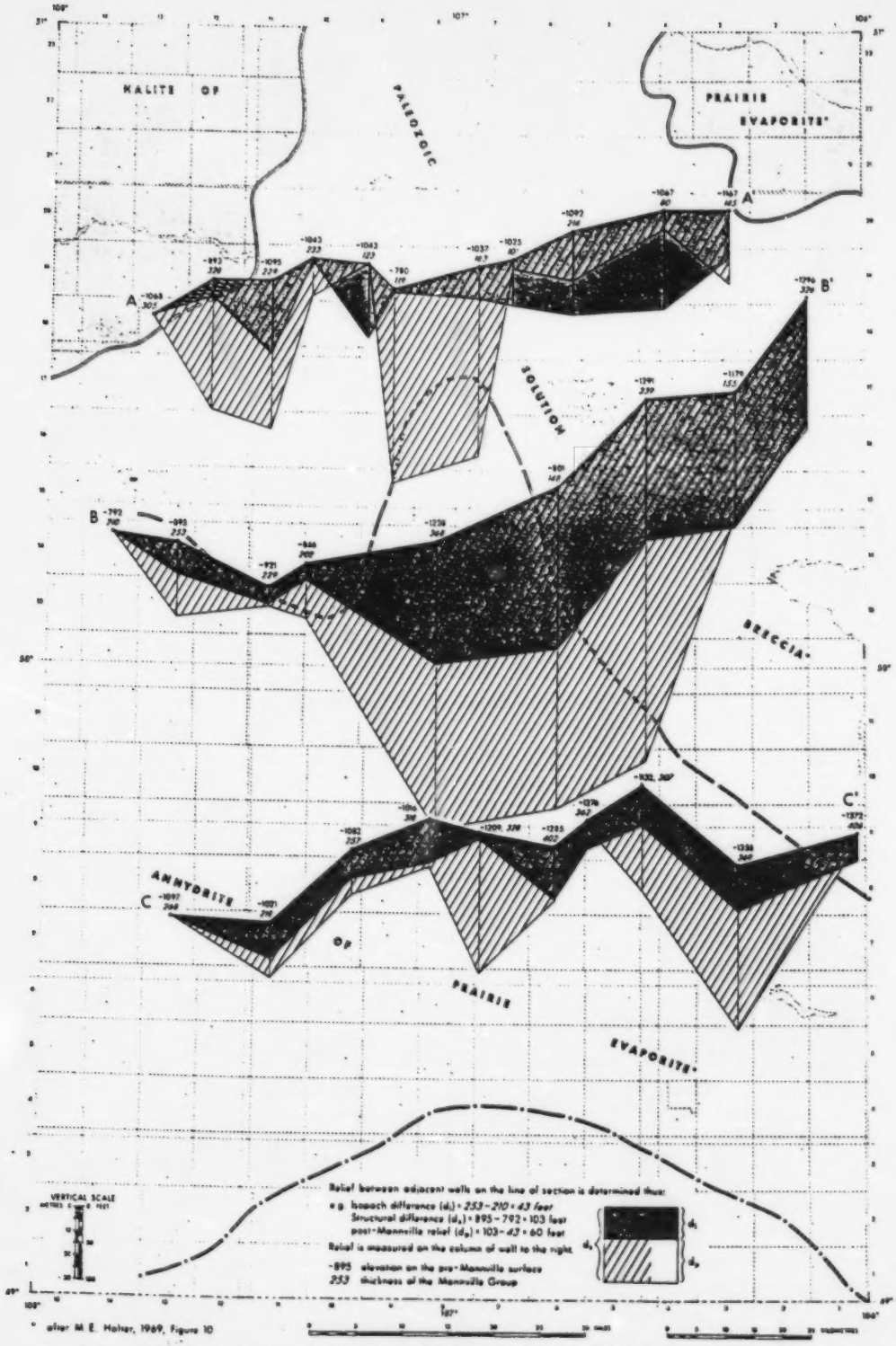

Figure 12- Plot of Mannville isopachous differences against structural relief on the pre-Mannville erosion surface, as taken between selected wells on the eastern flank of the Swift Current platform, Saskatchewan (after Christopher,1974).

repeated salt solution activities along the troughs over geologic time it would appear that movement on underlying basement lineaments is acting as the control.

Shorter linears, especially those detailed in the Vanscoy district more likely reflect a master joint system, whether or not they are topographic or structural. In Township 35 of Range 8W3, three northwesterly linears and one, perhaps two northeasterly ones are suggested in the 36 square mile (93.2 km^2) area. This does not appear to be an ultimate density for linears in the area. Three dimensional reflection seismic time-slices of the Lloydminster unit in the locality immediately to the northeast of the map area indicate 7 such linears trending northwest and 2 bearing northeast in a 3½ square kilometre area (Fig.13). This may be an upper limit, for the Mannville sandstones and shales being somewhat ductile, lack the brittle competency of the Paleozoic and Jurassic carbonates, and are therefore less likely to display a small scale checker board joint pattern.

THE HYDRAULIC SYSTEM

POTENTIOMETRIC HEAD

Headwaters of the Mannville Formation water-drive can be traced to the outcrops in the Rocky Mountains of central Montana. These are the Big Snowy-Belt Mountains and their subsidiaries to the north (Judith, Mocassins, Little Rockies, Bearpaws and Sweetgrass-Cypress Hills). The water system forms a continuous phase that extends across Saskatchewan to discharge points along the edge of the sedimentary basin in central Saskatchewan and western Manitoba.

However, the Mannville Formation is only a secondary carrier for meteoric water inflow. The primary aquifers

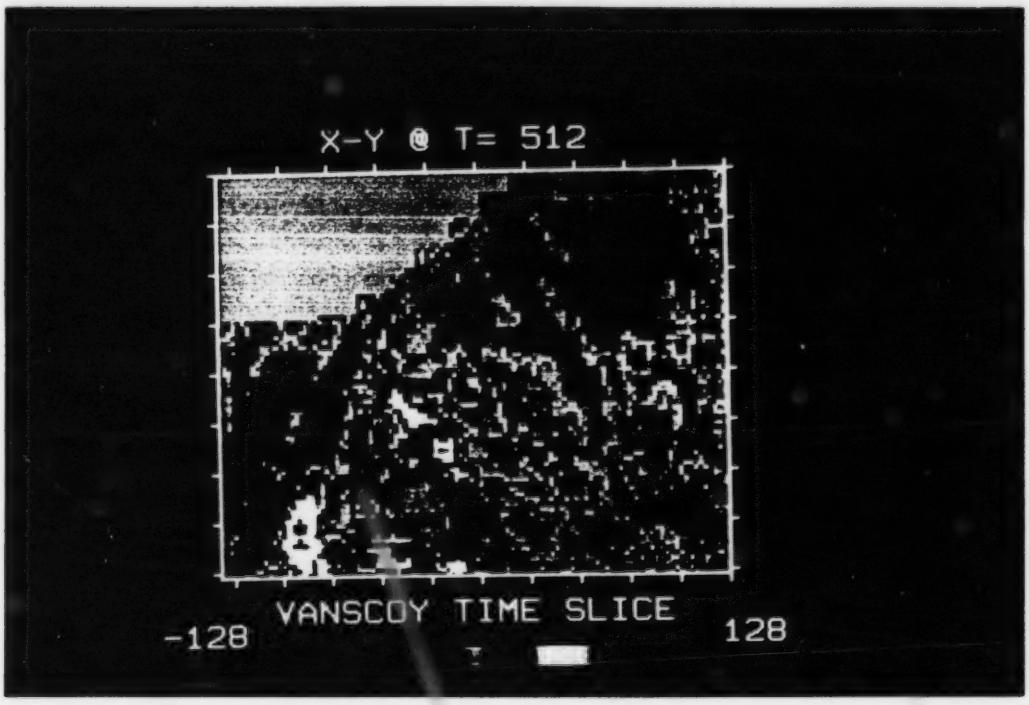

Figure 13. Display of linear elements in 3-D seismic time-slice of the Lloydminster unit. Area, approximately 3½km^2, Section 1. Township 36 Rge 8W3 (By permission).

are represented by the Mississippian Madison and Upper Devonian Jefferson (Birdbear and Duperow) Formations. These massive carbonate strata crop out at elevations of 1500m (5000 ft), and their potentiometric head descends toward southwestern Saskatchewan (Feltis, 1980). In southwestern Saskatchewan south of Maple Creek, Madison-Duperow waters at 824m (2700 ft) potentiometric head are piped into the Jurassic and Mannville Formations via fault-controlled fractures (Christopher, 1974).

From these potentiometric highs Mannville waters flow toward the northeast as a broad hydraulic sheet modified

by linear high pressure ridges marking other sites of cross-formational flow from the Paleozoic. A part of this regional system surrounding the study area is depicted in figure 14 (after Christopher, 1980).

As shown, the Mannville potentiometric surface in the region of Vanscoy and Cory lies at elevations of around 530m (1740 ft) to 500m (1640 ft). The district flanks the northern front of a broad higher pressure flat, keeled by the South Saskatchewan River and pressured by the drive from the southwest, as well as, by a high pressure ridge following the Elbow-Weyburn linear to the south.

In keeping with the southwesterly sourcing of meteoric waters, salinities in the Mannville and the Upper Paleozoic strata, which ranges from 40,000 to 80,000 ppm total dissolved solids at the Vanscoy district, freshen to less than one-third of that in southwestern Saskatchewan.

Vanscoy-Cory District

The potentiometric heads for the Mannville, Birdbear, Duperow, Souris River and Dawson Bay Formations as calculated from drill-stem tests are plotted in figures 15 and 16.

At the Vanscoy site all units of the Mannville (DST 6,5,9 and 10), as well as the Seward and Wymark Members of the Duperow Formation (DST 12 and 23) occupy the field of values between 518m (1700 ft) and 549m (1800 ft) and here called the isopotentiometric field. This relationship indicates hydraulic continuity between these formations.

A distinct increase of potentiometric elevation is displayed by the Birdbear (DST 22, 25), the Saskatoon Member of the Duperow (DST 26) and the lower half of the Souris River Formation.

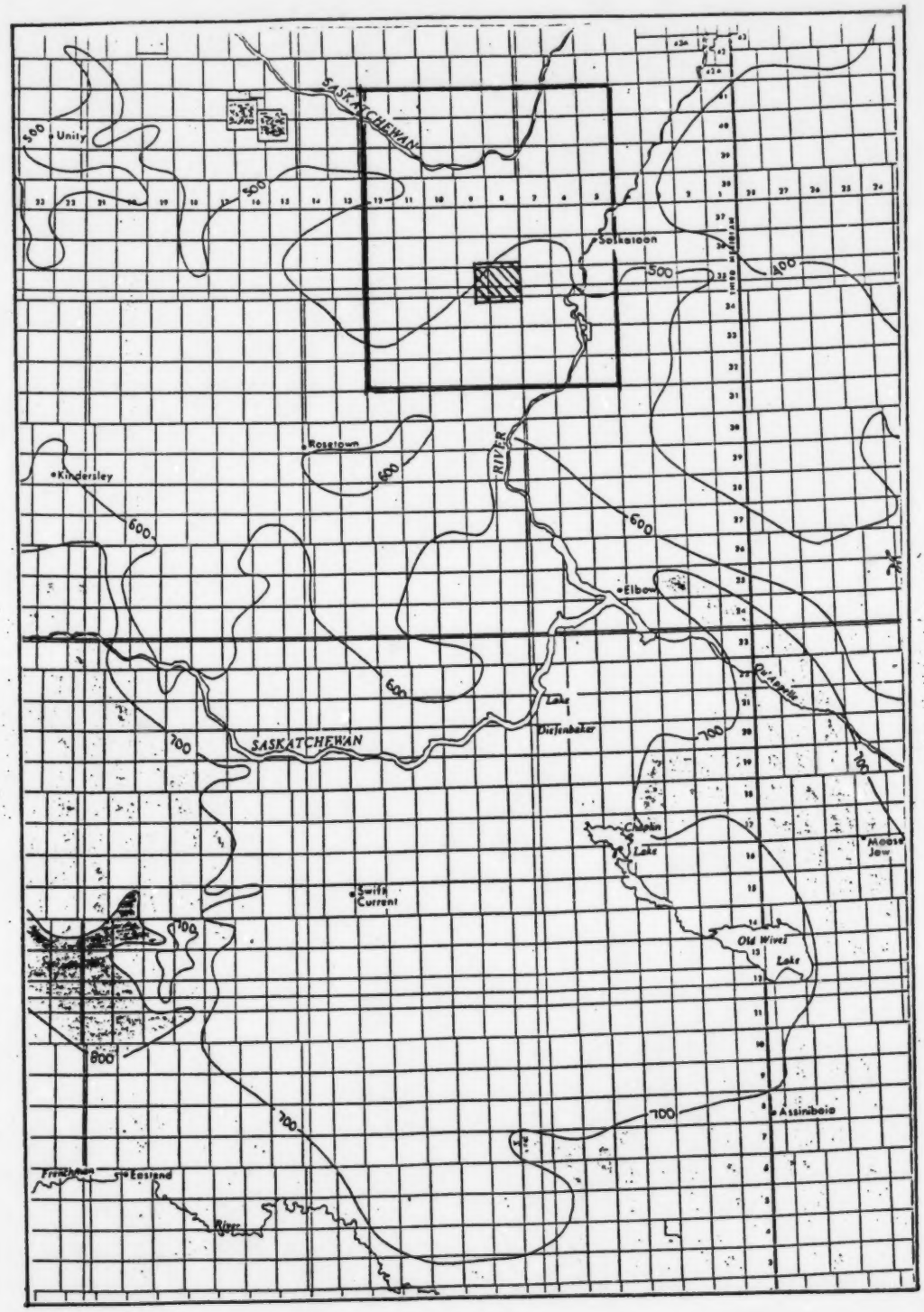

Figure 14. Potentiometric map of formation waters in the Mannville Group, southern Saskatchewan. Elevation in metres. (from Christopher, 1980)

The vertical field of values not withstanding, a secondary trend is also indicated by the empirical slope or isogradient line, drawn through the region of DSTs 6,9, 5,10,22 and 25. This line apparently represents the potentiometric loss from the lower formations to the higher. The gradient is calculated as 0.33 d, where 'd' represents the incremental increase in depth. This line if projected to the Dawson Bay Formation would indicate a head of 6[illegible]3m (2240 ft).

However, a parallel line drawn through the area of DSTs 12,23,26 and 15, i.e., the lower part of the Duperow Formation reveals a negative displacement of 42.7m (140 ft). It would appear that the mass of Souris River carbonates and evaporites is acting as a semipermeable barrier to vertical fluid exchange. Whereas that of the Seward and Wymark Members of the Duperow Formation does not. This is reflected in the salinity plots, wherein the total dissolved solids above the Souris River Formation are substantially less and range in magnitude from 37,700 in the upper Mannville to 103,500 ppm in the Duperow, versus the more than 252,000 ppm in the Souris River Formation.

The potentiometric head of the Waseca unit (DST 5) of the Mannville Formation, though lying in the isopotentiometric field, plots well above the isogradient. The displacement may reflect the nature of the Waseca, which at the Vanscoy site is made up of fluvial channel-sandstones with a high claystone matrix and encapsulating bodies limited in permeability and storage capacity. However, as reported from the shaft hole descriptions of Price and Ball (1973, p 89), the unit is multiple-faulted and jointed. The overpressure may therefore be a consequence of water inflows from underlying units. The other unit described as microfaulted is the more permeable Lloydminster which records the same head (DST 10).

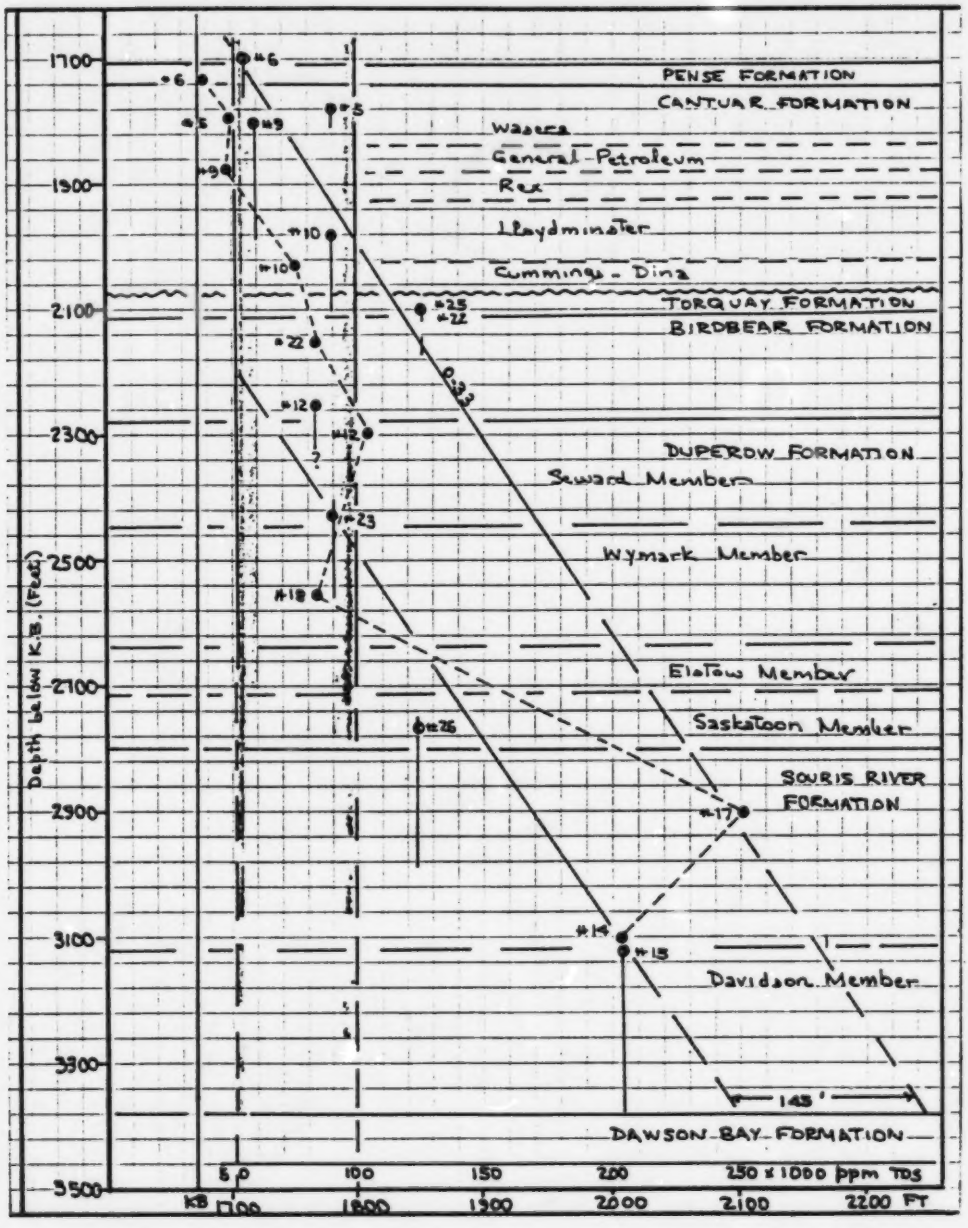

Figure 15. Potentiometric heads (fresh water) vs depth (ft) ⊗ ;
Salinity (TDS) vs depth (ft) ⊙
CM&S Vanscoy 11-16-35-8W3; KB elev. 1675 ft (510.5m)

With respect to the potentiometric elevation in the Birdbear Formation (DST 22), which plots on the isogradient but well above the isopotentiometric field, the explanation may lie in its post-depositional lithological history; i.e., late diagenesis. The upper part of the Birdbear Formation at this locality is composed of a microsucrosic dolomite featuring vugs and cavities partially clay-infilled, and coated with calcite druse, as well as calcite-infilled joints and fractures. The karsting represented by the cavities occured most likely in relation to the pre-Mannville unconformity. The calcite infilling seems to be a product of the contemporary formation water system in its early stages. Porosity is high, but permeability is controlled by the microporous matrix and the fractures opened by the karsting. Therefore, the 366m (1200 ft) of water released in the drill stem test may have been a relict of a former higher pressure body sealed in by the late diagenetic mineralization.

At the Duval Saskatoon 6-18 site (Fig.16) the isopotentiometric field is narrower than at Vanscoy 11-16, being only 22.9m (75 ft) wide. It includes all drill stem test values for the Pense, Cantaur and Birdbear Formations as well as the Seward and Wymark Member of the Duperow Formation.

Likewise, the 0.33 d isogradient satisfies all potentiometric elevations from the Mannville Formation (DSTs 7, 9,10,11 and 12) with the exception of DST 8. As at the Vanscoy site, departure from the isogradient occurs below the Wymark Member. The negative shift is 102m (335 ft), i.e., some 61m greater than at Vanscoy.

Similarly, the salinities of formation water from all units above the Souris River Formation lie between 46,000 and

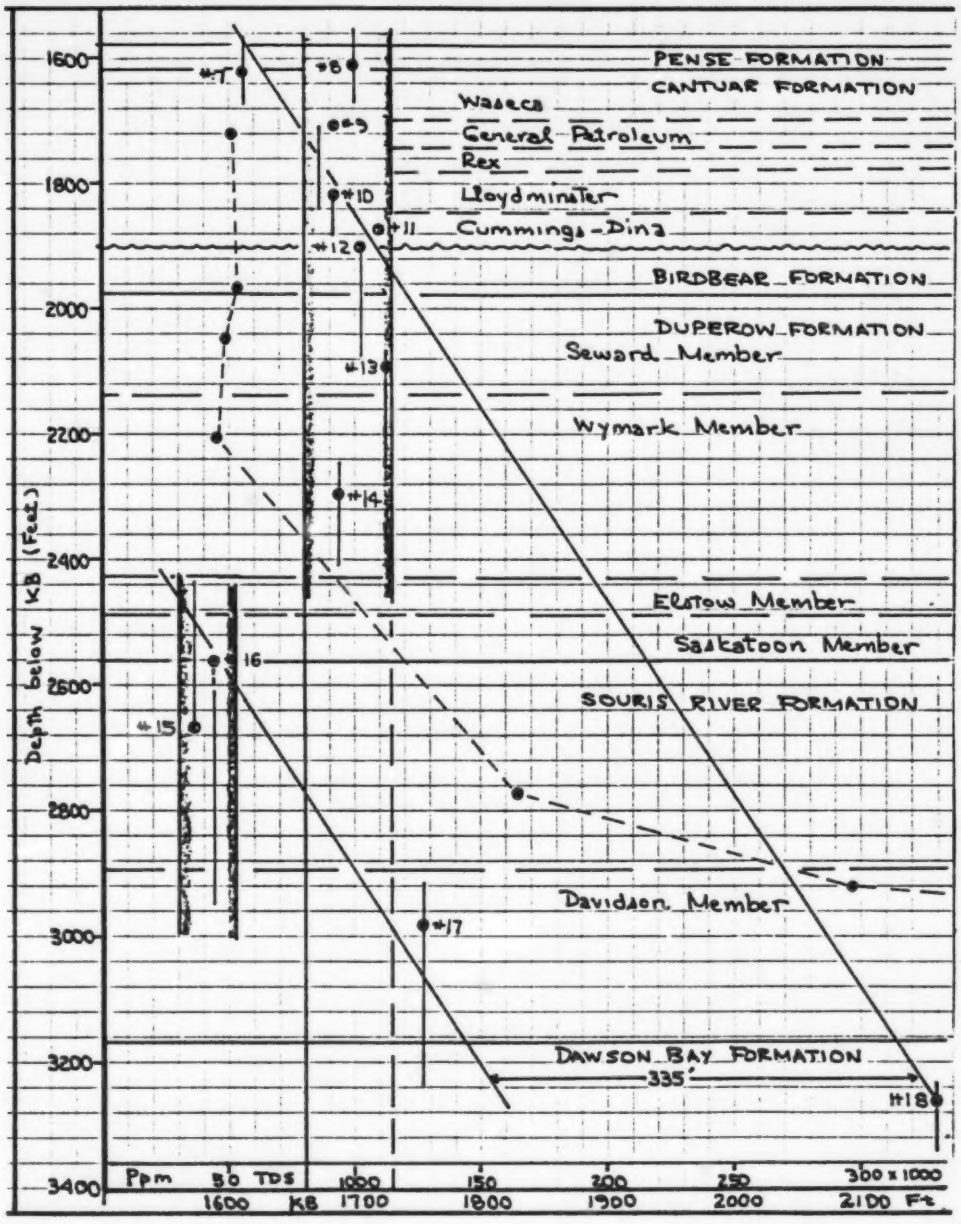

Figure 16. Potentiometric heads (fresh water) vs depth (ft)⊗, Salinity (TDS) vs depth (ft)⊙
Duval Saskatoon 6-18-36-6W3; KB Elev. 1659 ft (505.7m)

and 53,800 ppm total dissolved solids. In the Souris River these values increase abruptly to 256,000 and 393,000 ppm and in part, reflect proximity of the Davidson halite beds.

Though drill stem test no.7 lies along the isogradient, at an elevation of 1612 ft (491m), it plots at 15m (50 ft) below the isopotentiometric field. Yet drill stem test no.8 of the same interval came in at 1697 ft (516.9m), which places it well within the isopotentiometric field. Both tests seem valid, and it would appear that the local body of Pense sandstone, though under-pressured at the time of DST 7, may have been disturbed sufficiently to open communication with underlying units by the time of DST 8.

Formation Water Flow

At the Vanscoy well only the Cantaur and Birdbear of those formations above the Prairie Evaporite record a significant, i.e., 300 to 580m rise of water in the drill stem tests (Fig.17). At the Saskatoon well they are the Pense and Cantaur Formations and Wymark Member of the Duperow Formation. The highest of the water columns rise to within 30 to 60m of the ground surface elevation of 506m.

Although the plot of water columns between the two localities indicate a common hydraulic system, spatial and vertical lithogical variability will restrict or amplify volumetric capacity. By virtue of their marine character, sands of the Cummings, Lloydminster, Rex and General Petroleum units tend to be spatially consistent in terms of productive capacity (DSTs 9,10 and 11 at Saskatoon).

However, these sandstones are locally transected by channel sandstones of poorer permeability, and which therefore may form a flow barrier at one site or another. A major such barrier is indicated in the total isoporosity map of the sub-Waseca Mannville (Fig.10) running south to north in

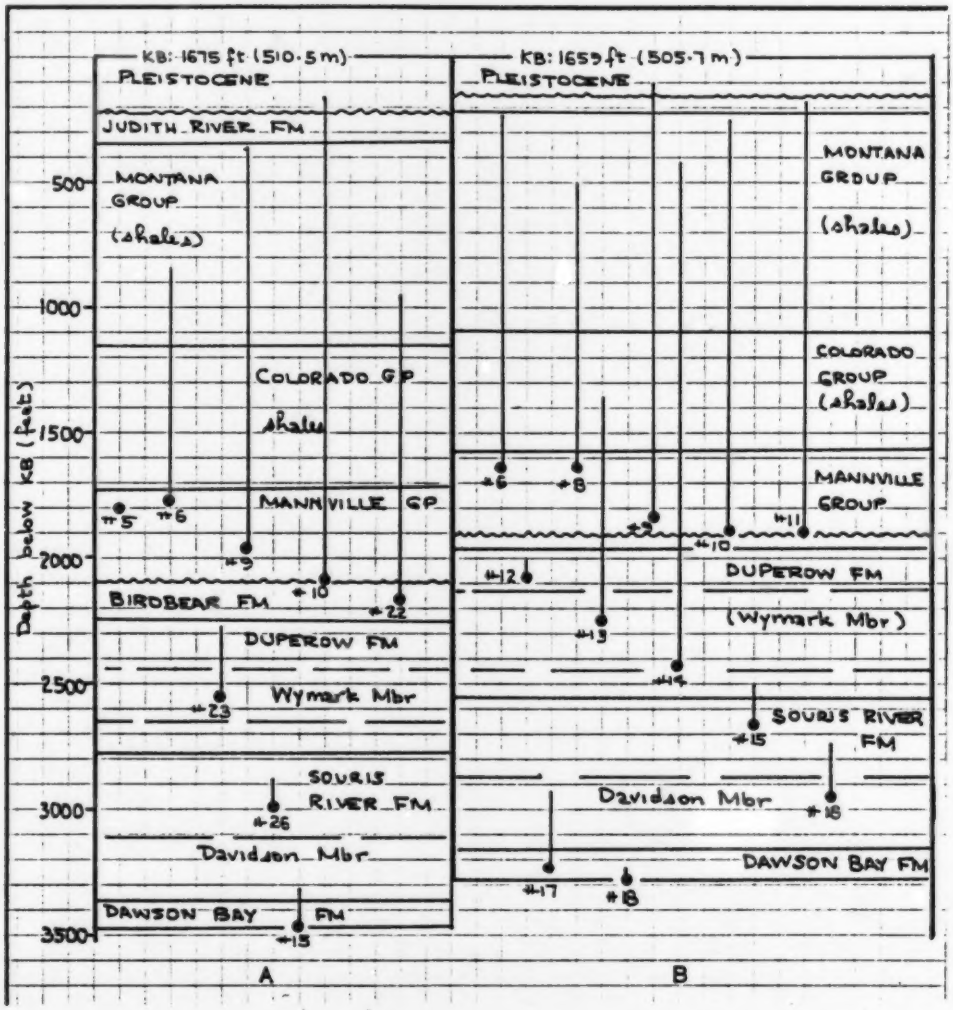

Figure 17. Rise (ft) of formation water in drill stem tests of the Mannville and the Devonian strata at (A) CM&S Vanscoy 11-16-35-8W3 and (B) Duval Saskatoon 6-18-36-6W3 wells.

Range 8W3 of the Cominco district. The Waseca unit, by virtue of its more fluviatile character in the region, is variable in water productivity (DSTs 5 and 6, 6 and 8 respectively).

Much of the better permeabilities in the Birdbear and upper part of the Duperow Formation are dependent upon solution-pitting and moldic porosity in otherwise bioclastic occluded limestones. Thus porosity is variable, and enhanced permeability is probably linked to unsealed fractures.

Thus distribution of permeability values from well to well is more site specific than regional. Water recoveries from these Devonian strata range from insignificant to 600m.

The potentiometric difference from the Vanscoy well to the Saskatoon well in the Wymark Member is -29m versus the -21m in the Lloydminster unit. The salinities are similar and so is the potentiometric difference. However, the small difference in elevation increases to-95m in the upper part of the Souris River Formation and -79m in the lower. The steepening of the hydraulic gradient to 4.9m/km and the overall negative shift of the pressure gradient line through the Souris River Formation (Figs. 14 and 15) of 46.7m at the Vanscoy site and 102m at the Saskatoon well, indicate a drainage of these lower units toward a potentiometric sink; presumably, the Saskatoon structural low or its subsidiary in the region of Range 6W3 (Fig.12). The reduced impact on the Mannville Formation water drive indicates integrity of the Souris River carbonates as an aquiclude.

As measured in the Lloydminster, Rex and General Petroleum units (DSTs 9 of the Vanscoy and Saskatoon wells) the potentiometric head, calculated to Fresh Water, falls from 534m (1754 ft) at Vanscoy to 513m (1685 ft) at the Saskatoon well, for a decline of 21m over the distance of 19.2km. This establishes a gradient of 1.20m/km toward to northeast.

The rate (V) at which the front of the water mass moves from A to B is dependent on the effective permeability of

of the aquifer.

The formula for rate of flow; i.e., hydraulic conductivity is given by

$V = \frac{K\rho}{\mu} \cdot \frac{d\phi}{d\Delta}$ where V = rate per unit cross-section (cc sec/cm^2)

K = permeability in Darcies (cm^2)

ρ = density (g/cm^3)

μ = viscosity in centipoises (g/cm/sec)

$\frac{d\phi}{d\Delta}$ = potentiometric gradient (cm/sec^2)

For saline water ρ/μ (kinematic viscosity) approximates 1. Thus V varies as permeability times the hydraulic gradient.

Permeability is an elusive quantity, The effective permeability as determined from the calculated transmissibility factor of 14,022 md/cp in DST 9 at the Vanscoy well over the 172 ft (52.3m) interval of the test is 81.5 md (internal document). An inspection of the gamma-ray-neutron-sonic log configuration indicate that of this total, only 79 ft (24m) of the sandstone-mudstone sequence would contribute the bulk of the water production. Thus the effective net permeability of the productive beds more nearly approximates 178 md.

Air permeability anaylses of 5 core plugs from the General Petroleum, Rex and Lloydminster units show a permeability array of 526, 245, 61, 33 and 16.8 md for the beds with porosity greater than 20 percent. The average air permeability when weighted against bed thickness from the log is 198 md. An average of the two values is 188 md.

Thus $V = .188 \times 1.20 \times 10^{-3}$

$= 2.26 \times 10^{-4}$ cm/sec

= 72.27m/yr

Another way to look at hydraulic conductivity is in terms of the volume of water moving under the hydraulic

gradient per given cross-sectional area of the Mannville reservoir units. An average porosity thickness in Township 35, Range 8W3 as estimated from the map of figure 10 is 10m; a section width is 1609m. Thus cross-sectional area equals $16,090m^2$.

The quantity of water moving across the section would be

$$2.26 \times 10^{-6} m/sec \times 1.61 \times 10^4 m^2 \times 60 \times 60 \times 24 \text{ day/sec}$$
$$= 3,144 m^3/day$$

Salinity, Density and the Formation Water Head

Potentiometric heads are calculated to fresh water equivalent heads, with density of fresh water equal to $1/g/cm^3$. However, the density of water increases with increasing concentration. Thus salinity affects the actual rise of water in the drill stem test. In none of the tests does formation water rise to the calculated fresh water head. However, because of other factors such as poor permeability of the test zone and formation drainage affecting the flow of water, a one-to-one relationship with salinity variation is not obvious.

The Mannville waters with their salinity in the range of 46,500-53,800 ppm total dissolved solids have densities of 1.028 and 1.038 g/cm^3. The calculated potentiometric head accordingly falls by 15.2 and 20.6m, i.e., to 518.8 and 513.4 from 534m. For the higher salinities, such as 162,876 and 286,211 ppm TDS of the Souris River Formation, the densities are 1.104 and 1.186 g/cm^3. The related calculated potentiometric heads are 471.5 and 436.2m. These are decreases in elevation of 52.7 and 88.1m. The relationship between actual potentiometric elevations and salinity is noted by Bachu et al (1987, p.843), who also observes that water density increases above that of fresh water at atmospheric

pressure are also related to the depth at which the formation lies.

Another characteristic of brines in an environment of mixed salinities should be noted. Where a brine overlies less saline water, the hydrostatic pressure gradient produces diffusion of the brine in the direction of increasing salinity (Sonnenfeld, 1984, p.53), and as well, increasing dynamic viscosity. Thus brines tend to move downward. The fact that salinity of formation water increases drastically in proximity to the Devonian salt beds is only a part of the equation.

THE SURFICIAL AQUIFERS

There are two major surficial aquifers in the region. Basal to the ground water system and the larger, sands of the Tertiary Empress Formation and the Late Cretaceous Judith River sandstone form a continuous phase linked to the Tyner-Battleford sub-glacial valleys (Fig.18). As detailed by Christiansen et al. (1970), the ground water flow is from southwest to northeast and is in partial communication with the South and North Saskatchewan Rivers.

Longitudinal flow along the Tyner Valley is estimated at a minimum of 5×10^6 gallons or 22,730 m^3 per day. Recharge is by surficial infiltration and regional inflow from the southwest in the Judith River Formation. Salinity is about 2450 ppm TDS.

The Dalmeny aquifer is an intraglacial unit between the subjacent Sutherland and the overlying Saskatoon glacial till. It comprises interbedded sand, silt and clay 30m and more thick and distributed northwest of Saskatoon in the area of the Tyner-North Battleford valley confluence. Hydraulic conductivity of the sand is 3×10^{-2}cm/sec. Recharge occurs

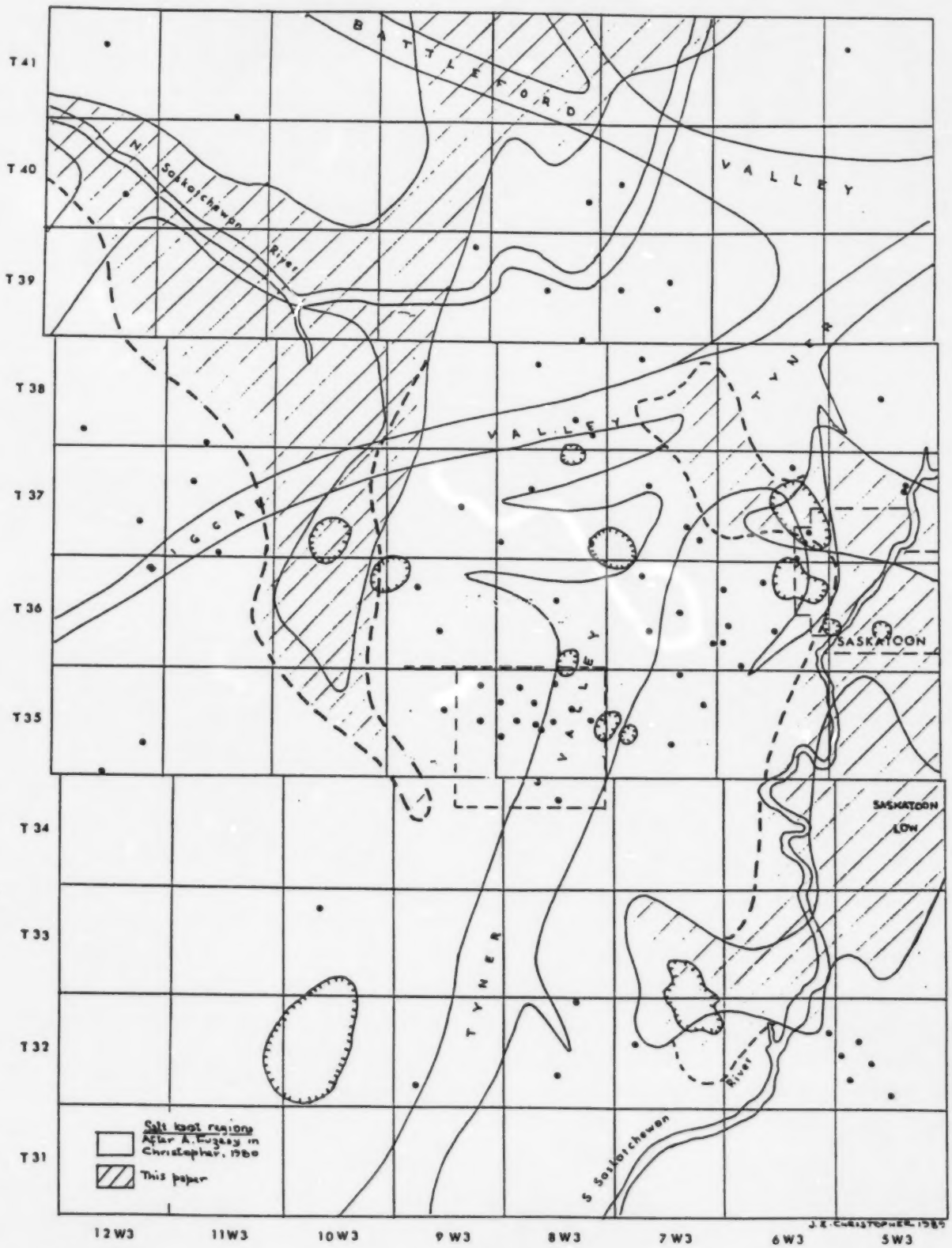

FIGURE 18
DEVONIAN SALT KARST & DRAINAGE
VANSCOY CORY REGION
SASKATCHEWAN

Scale 1:250,000 Échelle

by downward infiltration. Water flow is northwesterly into the walls of the North Saskatchewan River. Outflow is about 22,700 m^3/day, with some input by downward infiltration to the Empress-Judith River sands. Salinity ranges from 1600 to 2780 ppm TDS.

STRUCTURAL-TEMPORAL RELATIONSHIPS

A comparison of the rather large Tyner-Battleford valley system with the structure map at the sub-Mannville unconformity (Fig.11) shows no obvious relationship. In fact, the valleys link all of the structural terraces in the region west of the South Saskatchewan River, crossing the intervening depressions at near right angles. A possible exception is the district north of the city of Saskatoon where pre-Mannville sinks are known, and a tributary valley opening north, joins the Tyner in a widened basin.

On the other hand, the courses of the contemporary North and South Saskatchewan Rivers across the region are strongly constrained by elongate depressions depicted on the structural map. This is even true of Eagle Creek which joins the North Saskatchewan River from the south in Range 10W3.

The evidence is consistent with Christiansen's (1967) dating of the large depression south of Saskatoon as post-Cretaceous, and in fact, largely Pleistocene; with several episodes of collapse, the last of which was 12,000 years ago. The presence of 76m of stratified lacustrine silt and clay indicates accelerated salt solution effects during periods of glacial ice retreat, when vast quantities of water were released to the aquifer systems, including those of the Mannville and the Paleozoic.

The potentiometric field now existing in the Mannville

and more particularly, the Devonian Formations appear to be decayed versions of the earlier systems responsible for the massive karsting of the salt beds in the region. An analogy would be the great cave systems of the central and south-western United States. These appear to have undergone development by earlier cave filling water-dissolution cycles, followed by the current cycle of etching in the abandoned upper levels by joint controlled drip, stalactite growth, lower level stream flow and eventual cave collapse.

If the transfer of salt by dissolution from deeper strata cross-formationally to the surficial aquifer system is a current phenomena, the region of study would be a prime locale for it to appear. As extrapolated on the map of figure 18, salt removal action has made deep inroads on the mass of the Prairie Evaporite. Additional 10 known sinks are scattered across the region. So far no piping of saline water to the surficial aquifers has been reported. However, at 2500 ppm their water salinity is at about the upper limit for farm use in the southern Prairies. Higher salinities are not unusual. East of the study region, Lsd 8, sec 32, Twp 5 Rge 4W3, water salinity of 8200 ppm TDS is reported. The well is in the Judith River Formation, there downfaulted from459 to 378m (Christiansen, 1976).

SUMMARY OF GEOLOGICAL FACTORS

1. RESERVOIR PROPERTIES

The Mannville Reservoir bodies in the Vanscoy district are restricted to the Cummings, Lloydminster, Rex and General Petroleum units. They occur in permeable sandstone bodies that are broadly lenticular, but shingled so as to

form continuous beds. Those of the Cummings and General Petroleum units trend northwesterly and are best developed west of the CM&S Vanscoy 11-16-35-8W3 well. The Lloydminster and Rex units form a central body distributed bicamerally east and west of the 11-16 well. Total acessible reservoir volume for the district involving 54 sections of land is estimated at $1.04 \times 10^9 m^3$.

2. STRUCTURE

a. The major structural form is a monocline, dipping southwesterly and dissected into terraces by northwesterly and northeasterly troughs. In this context the Vanscoy-Cory district occupies the southwestern edge and northeastern crest respectively of a trapezohedral terrace elongated to the southeast. Dip is 2.7m/km to the southwest.

b. Control of the distribution of Mannville sedimentary bodies, differential structural movement, as well as the course of the major streams, are exercised by linear elements defining the Vanscoy-Cory terrace. These trend $N50^{\circ}W$ and $N50^{\circ}E$. An associated joint system is widespread.

c. Both large and small structural forms are pre-Mannville and have a relief of 35m. Post-Mannville changes are deepening of the troughs by some 120m and northerly expansion of their extent. These changes are attributed to subsidence of Devonian and Mannville strata into depressions created by removal of underlying Prairie Evaporite salt beds.

d. The last major karsting of the salt beds occurred in the Pleistocene Epoch apparently in response to the high volume flow-through from the melting of ice sheets related to the 5 stages of glaciation, the latest of which ended 12,000 years ago.

3. HYDRAULIC REGIME

a. The hydraulic system of the Mannville is shared in common with the Middle Member of the Duperow Formation (Wymark Member). The system possesses a common spread of potentiometric readings and salinities, as based on the drill stem tests from CM&S 11-16-35-8W3 and Duval Saskatoon 6-18-35-8W3 wells. It is separated from the surficial aquifers by 400m of Cretaceous shales and is floored by the dense limestones of the Devonian Souris River Formation.

b. Effective permeability of the Mannville reservoirs in the Vanscoy district is calculated to be 188 md and hydraulic conductivity at 2.3×10^{-4}cm/sec. Water flow is toward the northeast and estimated at $3{,}144 m^3$/day across the 1609m-width of a land section.

CONCLUSIONS AND RECOMMENDATIONS

1. Because of the close spacing and number (23) of Vanscoy wells, the chances are, that the porosity units are continuous as mapped and therefore reservoir capacity is more than adequate for the requirements of a pilot.

2. Volume for volume replacement of Mannville waters with brine will not increase the potentiometric levels of the formation water column, but would lower it at the storage site.

3. Brine as a dense medium may move northeast on the potentiometric slope but at a rate reduced by as much as 20 percent.

4. Brine emplaced on the flank of a trough may or may not move up-dip, but more likely may seep downward along the fractures to the Wymark Member of the Duperow Formation.

5. Total capacity of the reservoir units for storage of waste salt will depend on the amount of salt the formation water can absorb above its present base of 50,000 ppm TDS. This needs to be determined.

6. Should the Vanscoy site prove inadequate for complete disposal of current salt waste piles and production increments, potential supplementary sites are located on the other structural terraces to the south, west and north. Some are listed as follows:

Well Name and Location	Reservoir Thickness (m) (at 30% porosity)
a. H B Donavon 5-20-32-7W3	32 (8)
b. Freeport Sulphur Grandora 13-22-36-8W3	15.2 (3)
c. Pheas. Banff Dumferline 16-20-37-8W3	15.2 (3)
d. Sohio Red Creek Arelee 14-11-37-12W3	21.9 (7.3)
e. NPC Asquith 13-14-37-9W3	24.3 (8.1)

IMPACTS

1. Volumetric increase accompanies brining. Excess should be disposed of elsewhere than in the Mannville, because of the pervasive fracture system and relatively

high water columns. Over-pressured saline water might enter the surficial water system.

2. Brine disposal-reservoir when full may increase loading on abandoned galleries of the mine and thereby become a threat to the mine.

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